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RESEARCH MEMORANDUM

USE OF FLAME-IMMERSED BLADES TO IMPROVE COMBUSTION LIMITS AND EFFICIENCY OF A 5-INCH DIAMETER CONNECTED-PIPE, RAM-JET COMBUSTOR

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NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

WASHINGTON

April 9, 1953

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USE OF FLAME-IMMERSED BLADES TO IMPROVE COMBUSTION LIMITS AND EFFICIENCY OF A 5-INCH DIAMETER, CONNECTED-PIPE, RAM-JET COMBUSTOR

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SUMMARY

The effects of flame-immersed blades on combustion stability and efficiency were determined at various combustor-inlet conditions by using several geometrical blade arrangements, two fuels, two fuel-injection systems, and two blade temperatures. Flat blades, $3\frac{1}{2}$ by $\frac{13}{16}$ by $\frac{1}{8}$ inches, were immersed in the flame zone downstream of a conventional V-gutter baffle in a 5-inch-diameter, connected-pipe, ram-jet combustor.

Specific combustor configurations with flame-immersed blades showed marked improvement in stability and efficiency. The surface temperature of the immersed blades exhibited a second-order effect on the combustion stability and efficiency, thereby indicating that the role of the flame-immersed blades was primarily aerodynamic in character rather than thermal. Attempts at duplicating the benefits of flame-immersed blades by other means such as by variations in the gutter dimensions or by upstream-air vortex generation were unsuccessful.

The combustion efficiency of a burner configuration containing blades designed to increase mixing of the flame with fresh mixture downstream of the V-gutter flame holder was improved over that of a V-gutter alone. In addition, the combustion efficiency of this configuration was less sensitive to pressure than that of a V-gutter flame holder alone for the range of pressures investigated (0.45 to 1 atm).

INTRODUCTION

In the current efforts to improve ram-jet combustor performance, major emphasis has been placed upon the design of components upstream of the flame such as flame holders, fuel-injection systems, and other parts of the induction system; and relatively little has been done in the flame region itself. The combustion reactants are placed together in the combustion chamber, which affords space for reaction. In the case of baffle-type flame holders no assistance other than the recirculation zone of the flame holder is provided for the combustion reaction. In the case of the can-type combustor, somewhat more control of the addition of air or mixture to the burning gases is achieved by means of the axially spaced holes, but no aerodynamic control exists within the combustion space itself. The main reason for this is that materials that can survive in the combustion atmosphere are not readily available. It was feared that the reaction would be seriously quenched if materials were externally cooled.

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Combustion efficiency and stability can be affected by surfaces placed in the flame zone which are frequently called "flame-immersed surfaces" (refs. 1 to 3). An increase in the limits of combustion in a ram-jet combustor resulting from the addition of carbon wedges in the flame zone is shown in reference 1. Oxidation of the carbon limited the investigation to intervals of short operational time.

Improvement in the combustion stability of a single gutter achieved by filling it with ceramic material is briefly reported in reference 2. The performance of a 4- by 8-inch rectangular ducted ram jet with up to 12 gutters in tandem is reported in reference 3, page 9. While Inconel gutters, which melted during testing, were used in obtaining most of the data in reference 3, a newly developed material, molybdenum coated with molybdenum disilicide, was found sufficiently resistant to melting and oxidation to be satisfactory as a flame-immersed material; it therefore was selected for use in this investigation.

This report indicates how the combustion stability and the efficiency of a V-gutter flame holder can be affected by immersing flat blades in the flame. Several geometrical arrangements, two fuels (gasoline and isopentane), two fuel-injection systems, and two blade temperatures were used with various combustor-inlet conditions. The temperature of the immersed blades was varied to isolate the aerodynamic effect of the immersed blade from the combined aerodynamic and thermal effects.

The investigation was conducted at the NACA Lewis laboratory during 1952.

APPARATUS

The investigation reported herein was conducted in a 5-inch-diameter, connected-pipe, ram-jet combustor supplied with metered combustion air at a pressure of 55 pounds per square inch absolute. The combustion products were discharged to the laboratory exhaust system at a pressure of 2 pounds per square inch absolute (figs. 1 and 2). Sonic flow was maintained at the inlet air control unit shown in figure 1 to isolate any large pressure pulses occurring upstream in the supply system. The air mass flow was varied by moving a sleeve on the air control unit to vary the number of holes exposed to the air.

In order to obtain realistic ram-jet operating conditions, sonic flow was maintained with a two-dimensional variable-area exhaust nozzle (fig. 2). A metered water spray was introduced at the nozzle exit to quench the reaction and to permit determination of combustion efficiency by calorimetric methods.

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Clear gasoline or isopentane metered by a rotameter was injected 124 inches upstream of a V-gutter flame holder $1\frac{1}{2}$ inches wide by $1\frac{1}{2}$ inches high and was ignited by a momentary hydrogen-oxygen pilot in one end of the gutter.

The fuel injector consisted of two concentric tubes with two rows of 0.055-inch holes, drilled 180° apart, through both tubes. Fuel was supplied to the center tube and air to the annulus to atomize the spray. The fuel injector was mounted at the inlet of the diffuser perpendicular to the stream and oriented so that the fuel sprayed normal to the stream (fig. 2). For part of the investigation, a low fuel-injection pressure of about 10 pounds per square inch gage was used and, for the remainder of the investigation, a high pressure of 45 pounds per square inch gage was used.

Two types of blade were used (fig. 3); uncooled molybdenum blades protected from oxidation by a coating of molybdenum disilicide, and Inconel blades protected from melting by internal water cooling. Unless otherwise specified, the blades were uncooled. A maximum of 12 blades, $\frac{13}{16}$ by $3\frac{1}{2}$ by $\frac{1}{8}$ inches, were cantilever-mounted in the water-cooled combustor in various arrangements (fig. 4).

PROCEDURE

The combustion efficiency was determined by operating the combustor at equilibrium at a given condition with the quench water rate adjusted so that the temperature of the exhaust gases was 600° F. Efficiency calculations were based on the ratio of the total enthalpy rise over the theoretical enthalpy rise possible if all the fuel were completely burned.

Efficiency calculations were made according to the following equation:

$$\eta = \frac{\sum(\Delta H_w + \Delta H_e + \Delta H_j)}{(H_c)(f/a)} \tag{1}$$

where

η	combustion efficiency
ΔH_w	enthalpy rise of water used to quench exhaust gases, Btu/lb original air
ΔH_e	enthalpy rise of exhaust gases, Btu/lb original air
ΔH_j	enthalpy rise of cooling jacket water, Btu/lb original air
H_c	lower heating value of fuel, Btu/lb
f/a	fuel-air ratio

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and where for mixtures richer than stoichiometric:

$$\Delta H_e = \Delta H_s + \left[(f/a)_e - (f/a)_s\right]\left[(L_v)_{T_i} + c_p(T_e - T_i)\right]$$

where

ΔH_s	enthalpy rise of stoichiometric mixture, Btu/lb original air
$(f/a)_e$	actual fuel-air ratio
$(f/a)_s$	stoichiometric fuel-air ratio
(L_v)	latent heat of vaporization, Btu/lb fuel
c_p	mean heat capacity, Btu/($^{\circ}$F)/lb fuel
T_e	temperature of exhaust gas, $^{\circ}$R
T_i	inlet mixture temperature, $^{\circ}$R

With this method of calculating combustion efficiency, it is not possible to attain values of 100 percent at fuel-air ratios in excess of stoichiometric.

Combustion limits were determined by gradually changing the fuel rate, or combustion pressure, from a condition of stable burning to a condition of no burning, a change which was definite and abrupt in all cases.

RESULTS AND DISCUSSION

The basic data for combustion limits and efficiencies discussed in this section are presented in tables I and II.

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Combustion Limits

Configurations I and II. - The combustion limits were determined for configurations I and II, illustrated in figures 4(a) and 4(b). Configuration I consists of a V-gutter flame holder alone and configuration II contains 12 molybdenum blades mounted in line with the V-gutter along the combustor axis and with the blade faces perpendicular to the axis. The data obtained at a combustor-inlet velocity of 220 feet per second and an inlet-mixture temperature of 200° F with isopentane and low-pressure fuel injection are shown in figure 5, in which the limits of combustion are plotted as functions of inlet pressure expressed in atmospheres and fuel concentration expressed as equivalence ratio, that is, the ratio of actual fuel concentration to the stoichiometric fuel concentration. The presence of the uncooled blades considerably extended the operable fuel concentration range both rich and lean and lowered the minimum operating pressure from 0.57 to 0.35 atmosphere.

Geometrical variations. - Inasmuch as the data in figure 5 show that the combustion limits were improved by the immersed molybdenum blades, the limits were also determined with the blades for the various geometrical configurations shown in figures 4(c) to 4(f) with isopentane and low-pressure fuel injection.

In configuration III (fig. 4(c)), two-thirds of the blades were removed from configuration II so as to leave blades in the first, fourth, seventh, and tenth positions. Figure 6(a) compares the limits of this configuration with the limits shown in figure 5 and shows that the limits lie approximately halfway between those of configurations I and II.

Configuration IV (fig. 4(d)) is similar to configuration II but has the first six blades removed. The data showing combustion limits are presented in figure 6(b) (analogous to fig. 6(a)), and they show that configuration IV was less effective than configuration II. It is thus indicated that the blades have more effect on the stability limit when placed nearer the gutter than the exhaust end of the combustor.

In configuration V (fig. 4(e)), all 12 blades were used as in configuration II except that all the blades were parallel to the combustor axis instead of perpendicular. The data showing combustion limits are shown in figure 6(c) and indicate that the parallel configuration was less than half as effective as configuration II. This suggests that the aerodynamic effect was important in stabilizing combustion when the blades were perpendicular to the combustor axis.

In configuration VI, the 12 blades again were used but were turned at a 45° angle to the combustor axis with alternate blades turned in opposite directions as illustrated in figure 4(f). The results shown in figure 6(d) show that the minimum pressure limit was as good as for configuration II, but the equivalence ratio limits were slightly reduced.

It might be concluded from the foregoing discussion that the combustion limit was improved as the number of blades used was increased up to the number tested (12) and that the combustion limit was a function of the wake patterns of the blades and was poorest when the blades were parallel to the combustor axis.

Fuel type. - Inasmuch as isopentane, used in the foregoing tests, has a much higher vapor pressure than conventional jet-engine fuels, the combustion limits of configuration VI were also determined with gasoline. The data are shown in figure 7 along with the data for isopentane. The minimum pressure limit was the same for both fuels, and the lean side of the curve was approximately similar for both fuels; but the gasoline appeared poorer than the isopentane on the rich side, probably because the low-pressure fuel injector was used and poor atomization penalized the gasoline mixture more severely than the more volatile isopentane. The data are interpreted to mean that the reported trends are probably not fuel sensitive for petroleum fuels.

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High- and low-pressure fuel injection. - A study of the low-pressure fuel-injection system indicated that it did not deliver a completely homogeneous mixture to the combustor. A more nearly homogeneous mixture was obtained by increasing the atomizing air and fuel-injection pressure to about 45 pounds per square inch gage. The combustion limits of the V-gutter alone (configuration I) and of the in-line blades (configuration II), which are presented for the low-pressure injection system with isopentane in figure 5, were determined also for the high-pressure fuel-injection system with gasoline and are shown in figure 8. The data show that the high-pressure fuel injection improved the combustion limit of the V-gutter alone, but that the combustion limits of configuration II stayed virtually as shown in figure 5, indicating that the blades are more beneficial with a fuel system that does not give good spatial distribution than they are with a fuel system that does.

2-Inch gutter. - The isothermal pressure drop of configuration II was about 2.9 kinetic heads, which is 1 unit higher than that for the $1\frac{1}{2}$-inch V-gutter alone. Since increased stability sometimes accompanies increased pressure drop, an attempt was made to duplicate the combustion limits of the flame-immersed blades with a simple V-gutter flame holder by employing a wider V-gutter with a higher pressure drop. Consequently, the combustion limits of a 2-inch V-gutter with a pressure drop of 2.5 kinectic heads were compared with those of the $1\frac{1}{2}$-inch V-gutter used in all the other tests.

The data presented in figure 9 show that the combustion limits for the 2-inch V-gutter were poorer than for the $1\frac{1}{2}$-inch V-gutter. The decrease in stability was probably caused by the increased air velocity past the larger baffle. This is in agreement with the stability criterion, as reported in reference 4, which indicates that the optimum baffle-area blockage, with respect to combustion limits, occurs when the ratio of baffle area to gas velocity past the baffle is a maximum. According to this criterion, the optimum V-gutter width should be approximately $1\frac{1}{2}$ inches in a 5-inch-diameter duct.

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Effect of surface temperature. - The combustion limits of configuration II were determined with the water-cooled Inconel blades in order to separate the effect of hot surface from the aerodynamic effect, and these limits are compared in figure 10 with the data for configuration I and with the data for configuration II with uncooled blades. It can be seen that, while the limits of the cooled blades were less than those of the uncooled blades, the gain produced by the cooled blades was more than half that of the uncooled blades. Therefore, it appears that the blades in this position acted principally as aerodynamic baffles within the flame zone, and the surface temperature was of secondary importance in the stabilization mechanism. It should be noted that the closest blade to the V-gutter was $4\frac{1}{4}$ inches from it, and the surface temperature of any device closer to the V-gutter and immersed farther into the recirculation zone of the V-gutter may be of greater importance. The temperature of the uncooled molybdenum blades was as high as 2200° F, as indicated by optical pyrometer measurements.

The data show that noncritical materials can be used in a ram-jet design to improve performance because they can be cooled without severe combustion performance penalties.

The reproducibility of the combustion-limit data is indicated in figure 10 by check data for configuration I obtained on a different day.

Efficiency

Configurations I and II. - Configurations I and II were used to determine if the mere presence of hot incandescent surfaces (up to 2200° F) might affect the combustion efficiency. This was done at three sets of operating conditions as indicated in figure 11. For the data in figure 11(b) the hydrogen-oxygen ignition flame was left on in order to obtain the data for the V-gutter alone inasmuch as the conditions are below the combustion limits. Isopentane with low-pressure fuel injection was used.

For all the conditions investigated, the combustion efficiency of configuration II was essentially the same as or slightly higher than that of configuration I.

Flame and mixture mixing. - Visual study of the flame downstream of the V-gutter suggested that a more rapid mixing of flame into the fresh mixture was needed to improve combustion efficiency. For this purpose 12 blades were installed in the combustion chamber in a manner intended to mechanically mix flame with fresh mixture, yet far enough downstream of the V-gutter so as not to upset the basic stability of the flame in the gutter wake. The arrangement, configuration VII, is shown in figure 4(g). The blades were arranged in three equally spaced rows; the rows were parallel to the stream with four blades to each row in equally spaced positions, but each blade occupied a different station in an alternating fashion from row to row. Each blade was inclined at an angle of attack of 45° to the stream, and all blades were turned in the same direction so as to indicate a right-hand threaded system. 2678

The combustion efficiency of this configuration, shown as a function of equivalence ratio in figure 12, was 7 percentage points higher than corresponding data for a V-gutter alone at an equivalence ratio of 1 and 14 percentage points higher at an equivalence ratio of 0.8. The inlet conditions were pressure, 1.33 atmospheres; temperature, approximately 250° F; and velocity, 200 feet per second. Isopentane and low-pressure fuel injection were used for the data in figure 12.

Upstream vortex generation. - An attempt to match this increase in efficiency by imparting a vortex or swirl to the stream upstream of the baffle was made by installing two vortex generators 4 inches upstream of the baffle, as shown in figure 4(h), configuration VIII. These vortex generators were 1 inch wide and 3 inches long and inclined at a 10° angle of attack. The intended flow pattern was two contrarotating spirals in order to mix flame in the gutter-baffle wake with fresh mixture. The efficiency of configuration VIII is also shown in figure 12 and was less than 30 percent. The explanation is offered that the mixing occurred too soon, before the flame immediately behind the baffle was well established, and that mixing served more to quench the flame than to extend its propagation. This is supported by the fact that the combustion limits of configuration VIII, as indicated on the efficiency curves by the span of the curve, were much poorer than those of configurations I and II or VII.

Wider gutter. - Another attempt to duplicate the increase in efficiency achieved by configuration VII was made by increasing the baffle width from $1\frac{1}{2}$ to 2 inches since increased pressure drop can sometimes increase combustion efficiency. The resultant data with gasoline and the high-pressure fuel injector are shown in figure 13 and indicate that this change lowered the combustion efficiency approximately 5 percentage points.

The conclusion from the data in figures 12 and 13 is that aiding or speeding up the mixing process between flame and fresh mixture with concurrent increase in over-all reaction rate is readily accomplishable downstream of the flame-holding baffle, but is difficult to achieve upstream of the flame region without interfering with the stability.

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Cooled and uncooled blades. - The effect of the mixing blades of configuration VII was further investigated by determining the combustion efficiency with both cooled and uncooled blades. The data, which are presented in figure 14 along with the data for configuration I, were taken with gasoline and the high-pressure fuel injector at the following inlet conditions: pressure, 1 atmosphere; velocity, 200 feet per second; temperature, 200° F. The cooled blades produced approximately 80 percent as much increase in efficiency as the uncooled blades at an equivalence ratio of 1. These data seem to show that the aerodynamic mixing effect of the blades on combustion efficiency is great and the surface temperature effect, while appreciable, is notably less.

The significance of the foregoing discussion is that flame-immersed surfaces can be used in ram-jet combustor design to increase both combustion limits and efficiency, and also that noncritical materials can be assigned to this job since they can be cooled without severe performance penalties.

The improved combustion efficiency of configuration VII with the uncooled molybdenum blades compared with configuration I at a decreased inlet pressure of 0.67 atmosphere is shown in figure 15. The other inlet conditions were the same as those in figure 14.

Effect of pressure on efficiency with flame mixing. - The efficiency of configuration VII with uncooled molybdenum blades was investigated over a range of combustor-inlet pressures from 0.45 to 1 atmosphere with gasoline and the high-pressure fuel system. The resultant data are shown in figure 16.

The combustion efficiency data of reference 5 obtained for the same 5-inch-diameter combustor described herein with a V-gutter alone correlate with the inlet flow variables of static pressure P, temperature T, and velocity V by the empirical parameter $P^{0.3}TV^{-0.8}$. The exponents of the variables were determined by taking the slope of the straight-line correlation when combustion efficiency is plotted against the variables individually on logarithmic coordinates. If the combustion efficiency data for configuration VII are cross-plotted from figure 16 at an equivalence ratio of 1, the exponent of the pressure coefficient in this empirical parameter becomes 0.17 as compared with an exponent of 0.27 obtained from data in reference 5 taken with a V-gutter at comparable inlet conditions. Both sets of data are shown in figure 17. These data indicate that the combustion efficiency of configuration VII is less sensitive to inlet pressure than that of the V-gutter alone.

OPERATIONAL LIFE OF BLADES

The operational life of both types of blade was excellent for several hundreds of hours and did not limit the test duration except that at inlet air pressures above $1\frac{1}{4}$ atmospheres the molybdenum blades sometimes bent under ram pressure when incandescent.

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SUMMARY OF RESULTS

The following statements summarize the results obtained from operation of the 5-inch-diameter, connected-pipe, ram-jet combustor over the range of conditions investigated.

1. Flame-immersed blades improved combustion stability by extending the combustion limits, both rich and lean, and by decreasing the minimum permissible inlet pressure.

2. Flame-immersed blades improved combustion efficiency by improving the mixing of flame with fresh mixture downstream of a flame-holding baffle without upsetting the stability of the flame immediately behind the baffle.

3. Attempts at increasing the mixing of flame with fresh mixture by vortex generation upstream of the flame-holding baffle resulted in upsetting the combustion stability of the baffle, and lowered the efficiency.

4. The action of the flame-immersed blades used in this investigation on both combustion stability and efficiency was primarily aerodynamic inasmuch as the temperature of the blades showed secondary significance. Nonrefractory materials, externally cooled, were employed as immersed surfaces to improve combustion performance.

5. A blade configuration which mixed flame and fresh mixture in the combustor exhibited less sensitivity of combustion efficiency to inlet pressure than was found with a V-gutter flame holder alone.

6. Increasing the baffle width resulted in poorer combustion limits and efficiency.

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TABLE I. - BASIC DATA FOR COMBUSTION LIMITS SHOWN IN FIGURES 5 TO 10

Figure	Run	Air flow, M_a, lb/sec	Inlet static pressure, P, atm	Inlet mixture temperature, T, °R	Inlet velocity, V, ft/sec	Equivalence ratio	Blow-out	Fuel	Injection-system pressure	Configuration
5 and 6	165	0.781	0.377	615	230.2	1.159	Rich	Isopentane	Low	II
	166	.781	.377	615	230.2	.821	Lean			
	167	.779	.346	615	249.0	.966	Min. press.			
	168	.893	.473	615	209.7	.765	Lean			
	169	.893	.473	615	209.7	1.240	Rich			
	170	.893	.473	615	209.7	1.231	Rich			
	172	1.378	.733	641	217.4	1.349	Rich			
	173	1.390	.733	641	219.2	.680	Lean			
	180	1.99	1.033	648	225.1	.659	Lean			
	186	2.015	1.050	655	226.9	1.393	Rich			
	187	.818	.433	655	223.6	.784	Lean			
	188	.822	.433	655	224.7	1.151	Rich			
5	266	1.200	0.616	643	225.7	1.265	Rich	Isopentane	Low	I
	267	1.200	.616	660	231.6	.901	Lean			
	268	1.200	.616	661	232.0	.879	Lean			
	269	.990	.566	652	205.4	1.038	Min. press.			
	270	1.340	.716	637	214.8	1.271	Rich			
	271	1.360	.716	665	227.6	.830	Lean			
	274	2.025	1.016	640	229.9	1.333	Rich			
	275	2.025	1.016	667	239.6	.769	Lean			
	276	1.200	.716	645	194.8	1.298	Rich			
6(a)	200	0.817	0.433	609	207.1	1.109	Rich	Isopentane	Low	III
	201	.812	.436	617	206.9	.942	Lean			
	202	.812	.423	613	212.1	1.026	Min. press.			
	203	1.005	.536	600	202.7	1.222	Rich			
	204	1.005	.533	616	209.4	.881	Lean			
	205	1.005	.536	621	209.8	.853	Lean			
	206	1.400	.733	622	214.2	1.269	Rich			
	207	1.410	.736	648	223.7	.792	Lean			
	208	1.427	1.273	639	129.2	1.026	Max. press.			
6(b)	131	1.013	0.543	644	216.7	0.855	Lean	Isopentane	Low	IV
	136	1.370	.696	657	233.0	.720	Lean			
	139	1.360	.696	637	224.2	1.171	Rich			
	145	2.054	1.030	639	230.0	1.313	Rich			
	146	2.054	1.030	639	230.0	.699	Lean			
6(c)	189	0.918	0.483	601	205.9	1.141	Rich	Isopentane	Low	V
	190	.936	.483	609	212.7	.968	Lean			
	191	1.001	.533	609	208.2	1.194	Rich			
	192	.992	.533	624	209.4	.920	Lean			
	193	1.422	.733	606	212.0	1.289	Rich			
	194	1.447	.733	640	227.8	.798	Lean			
	195	1.970	1.040	651	222.4	.755	Lean			
	196	1.973	1.033	623	214.6	1.347	Rich			
6(d) and 7	209	1.444	0.737	599	211.7	1.313	Rich	Isopentane	Low	VI
	210	1.434	.737	627	220.0	.745	Lean			
	211	1.224	.640	610	210.4	1.289	Rich			
	212	1.224	.637	637	220.7	.740	Lean			
	213	1.429	.737	615	215.1	1.321	Rich			
	214	1.429	.737	643	224.9	.732	Lean			
	215	1.998	1.040	618	214.2	1.390	Rich			
	216	1.998	1.037	654	227.3	.687	Lean			
	232	.641	.367	606	190.9	1.161	Rich			
	241	1.995	1.040	663	229.4	.677	Lean			

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TABLE I - BASIC DATA FOR COMBUSTION LIMITS SHOWN IN FIGURES 5 TO 10 - Continued

Figure	Run	Air flow, M_a, lb/sec	Inlet static pressure, P, atm	Inlet mixture temperature, T, ^{o}R	Inlet velocity, V, ft/sec	Equivalence ratio	Blow-out	Fuel	Injection-system pressure	Configuration
7	217	1.416	0.737	605	209.6	1.214	Rich	Gasoline	Low	VI
	218	1.425	.737	639	222.9	.702	Lean			
	219	1.204	.637	616	210.0	1.246	Rich			
	220	1.230	.637	642	223.6	.732	Lean			
	221	1.448	.737	620	219.7	1.222	Rich			
	222	2.015	1.037	625	219.0	1.225	Rich			
	223	2.010	1.033	658	230.9	.633	Lean			
	224	1.183	.633	611	206.0	1.232	Rich			
	225	1.182	.633	636	214.2	.762	Lean			
	226	.802	.433	610	203.8	1.199	Rich			
	227	.819	.433	611	208.4	1.154	Rich			
	228	.819	.433	624	212.9	.855	Lean			
	229	.640	.367	591	185.8	1.178	Rich			
	230	.638	.367	603	189.1	.946	Lean			
	231	.643	.330	610	214.4	1.061	Rich			
	233	.639	.367	620	194.7	0.908	Lean	Isopentane	Low	VI
	234	.639	.338	613	209.0	1.044	Rich			
	235	.812	.433	618	209.0	1.216	Rich			
	236	.812	.433	634	214.4	.867	Lean			
	237	.812	.433	635	214.8	.847	Lean			
	238	1.170	.633	618	206.0	1.297	Rich			
	239	1.177	.640	644	213.6	.760	Lean			
	240	1.980	1.033	629	217.5	1.375	Rich			
8 and 10	457	1.955	1.000	650	229.2	0.741	Lean	Gasoline	High	I
	458	1.940	1.000	626	219.0	1.368	Rich			
	459	1.390	.700	654	234.2	.771	Lean			
	460	1.365	.700	636	223.7	1.294	Rich			
	461	1.150	.600	655	226.4	.815	Lean			
	462	1.190	.600	632	226.1	1.278	Rich			
	463	1.190	.600	633	226.5	1.252	Rich			
	464	1.175	.600	656	231.7	.798	Lean			
	465	1.000	.500	654	235.9	.816	Lean			
	466	1.005	.500	636	230.6	1.220	Rich			
	467	.890	.450	653	232.9	.866	Lean			
	468	.890	.450	639	227.9	1.152	Rich			
	469	.890	.450	638	227.6	1.180	Rich			
	470	.885	.400	649	259.0	1.008	Min. press.			
	471	0.985	0.500	650	231.0	0.711	Lean	Gasoline	High	II
	472	.995	.500	627	225.1	1.276	Rich			
	473	.885	.450	656	232.7	.724	Lean			
	474	.880	.450	631	222.6	1.274	Rich			
	475	.880	.450	634	223.6	1.254	Lean			
	477	.760	.400	640	219.4	1.233	Rich			
	478	.755	.313	655	284.7	.982	Min. press.			
	479	.760	.326	669	280.7	.882	Min. press.			
	480	.825	.400	677	251.8	.742	Lean			
	481	.850	.330	668	310.4	.873	Min. press.			
	482	1.185	.600	683	243.3	.664	Lean			
	483	1.150	.600	649	224.3	1.377	Rich			
	484	1.375	.700	687	243.4	.648	Lean			
	485	1.360	.700	652	228.5	1.382	Rich			
	486	1.930	1.000	683	237.8	.634	Lean			
	487	1.940	1.000	641	224.3	1.401	Rich			

NACA

TABLE I. - BASIC DATA FOR COMBUSTION LIMITS SHOWN IN FIGURES 5 TO 10 - Concluded

Figure	Run	Air flow, M_a, lb/sec	Inlet static pressure, P, atm	Inlet mixture temperature, T, °R	Inlet velocity, V, ft/sec	Equivalence ratio	Blow-out	Fuel	Injection-system pressure	Configuration
9 and 10	396	1.914	1.000	670	231.3	0.660	Lean	Gasoline	High	I
	400	1.914	1.000	636	219.6	1.398	Rich			
	401	1.425	.700	670	246.0	.684	Lean			
	402	1.425	.700	639	234.6	1.347	Rich			
	406	1.181	.600	660	234.3	.692	Lean			
	407	1.180	.600	659	233.7	.717	Lean			
	408	1.170	.600	628	220.9	1.353	Rich			
	409	.975	.500	660	232.2	.726	Lean			
	410	.975	.500	635	223.4	1.257	Rich			
	411	.875	.450	660	231.5	.767	Lean			
	412	.868	.450	638	222.0	1.241	Rich			
	413	.770	.400	639	221.8	1.206	Rich			
	414	.768	.400	659	228.2	.798	Lean			
	415	.768	.400	659	228.2	.803	Lean			
	416	.765	.343	652	262.1	1.019	Min. press.			
	417	.770	.358	651	252.4	1.110	Min. press.			
	418	.755	.333	659	269.3	.954	Min. press.			
	419	.768	.350	664	262.8	1.014	Min. press.			
	420	1.608	.850	659	224.9	1.394	Rich			
	421	1.610	.850	693	236.7	.652	Lean			
	422	1.650	.850	693	242.6	.652	Lean			
	423	1.655	.850	683	239.9	.672	Lean			
9	577	1.185	0.600	649	231.2	0.886	Lean	Gasoline	High	I[a]
	578	1.190	.600	632	226.1	1.244	Rich			
	579	.985	.500	639	227.0	1.062	Lean			
	580	.985	.500	640	227.4	1.088	Rich			
	581	.985	.510	641	223.3	1.074	Min. press.			
	582	1.090	.550	648	231.6	.952	Lean			
	583	1.090	.550	639	228.4	1.173	Rich			
	584	1.720	.850	675	246.3	.772	Lean			
	585	1.720	.850	649	236.9	1.316	Rich			
	586	1.990	1.000	675	242.3	.760	Lean			
	587	1.995	1.000	647	232.8	1.342	Rich			
	588	1.965	1.000	647	229.3	1.342	Rich			
10	424	1.920	1.000	656	227.1	0.756	Lean	Gasoline	High	II[b]
	425	1.920	1.000	627	217.1	1.380	Rich			
	426	1.370	.700	630	222.4	1.314	Rich			
	427	1.365	.700	630	221.6	1.324	Rich			
	428	1.370	.700	651	229.8	.888	Lean			
	429	1.350	.700	648	225.4	.934	Lean			
	430	1.198	.600	650	234.1	.904	Lean			
	431	1.202	.600	629	227.3	1.335	Rich			
	432	.955	.500	658	226.7	.816	Lean			
	433	.950	.500	638	218.6	1.228	Rich			
	434	.780	.393	649	232.2	.999	Min. press.			
	435	.780	.380	649	240.2	.999	Min. press.			
	436	1.130	.600	659	223.8	.789	Lean			
	437	1.130	.600	635	215.7	1.292	Rich			

[a]V-gutter 2" wide by 2" high.
[b]Cooled blades.

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TABLE II. - BASIC DATA FOR COMBUSTION EFFICIENCIES SHOWN IN FIGURES 11 TO 16

Figure	Run	Air flow, M_a, lb/sec	Inlet static pressure, P, atm	Inlet mixture temperature, T, °R	Inlet velocity, V, ft/sec	Equivalence ratio	Efficiency, η	Fuel	Injection-system pressure	Configuration
11(a)	59	3.80	2.003	684	234.0	0.769	65.2	Isopentane	Low	II
	60	3.80	2.013	685	233.2	.714	63.8			
	61	3.80	2.013	687	234.0	.660	61.6			
	62	3.79	2.010	680	231.2	.829	69.1			
	63	3.79	2.010	677	230.2	.885	70.9			
	64	3.79	2.000	674	230.4	.942	71.2			
	65	3.79	2.000	672	229.6	.997	70.9			
	66	3.79	2.000	668	228.3	1.055	66.6			
	67	3.79	2.000	666	227.7	1.108	62.8			
	68	3.79	1.993	681	233.6	.771	67.8			
	69	3.79	2.000	678	231.8	.885	72.2			
	70	3.79	2.000	676	231.0	.942	73.4			
	71	3.79	2.000	684	233.8	.716	64.6			
	72	3.85	2.000	673	233.8	0.760	62.1	Isopentane	Low	I
	73	3.84	2.000	670	232.1	.818	65.2			
	74	3.84	2.000	667	231.1	.873	69.6			
	75	3.84	1.993	663	230.5	.930	70.7			
	76	3.84	2.010	660	227.6	.985	70.4			
	77	3.84	2.010	657	226.5	1.040	66.1			
	78	3.84	2.007	655	226.0	1.096	59.3			
	79	3.84	2.007	660	228.0	.985	70.1			
	80	3.84	2.000	664	229.9	.930	70.8			
	81	3.84	2.000	668	231.3	.873	69.8			
	82	3.84	2.000	674	233.6	.760	63.9			
	83	3.84	2.000	674	233.6	.708	(1)			
11(b)	25	1.060	0.520	633	232.7	0.777	52.2	Isopentane	Low	I
	26	1.055	.516	626	230.5	.896	49.7			
	27	1.060	.520	621	228.4	1.005	46.9			
	28	1.060	.520	625	230.0	.950	48.7			
	29	1.068	.520	628	232.7	.835	50.3			
	30	1.068	.523	619	227.9	1.053	42.6			
	31	1.068	.523	618	227.7	1.110	40.0			
	32	1.072	0.520	614	228.3	0.992	47.6	Isopentane	Low	II
	33	1.058	.523	614	224.1	.950	50.6			
	34	1.070	.516	617	230.7	.884	52.5			
	35	1.067	.516	619	230.7	.827	54.0			
	36	1.066	.523	623	229.1	.773	56.4			
	37	1.069	.520	612	217.1	1.047	42.0			
	38	1.068	.520	609	226.0	1.116	38.2			
	39	1.068	.520	616	228.2	1.052	42.0			
	40	1.068	.520	621	230.5	.940	49.1			
	41	1.068	.516	626	233.6	.826	52.4			
11(c) and 12	11	2.020	1.326	728	200.1	0.821	76.6	Isopentane	Low	I
	12	2.030	1.343	721	196.5	1.018	76.7			
	13	2.005	1.326	710	193.5	1.261	57.0			
	14	2.025	1.330	729	200.2	.911	81.4			
	15	2.000	1.346	739	198.1	.721	79.2			
	17	2.020	1.330	718	196.8	0.811	77.2	Isopentane	Low	II
	18	2.026	1.326	711	196.0	1.020	75.8			
	19	2.009	1.333	709	192.8	1.137	69.7			
	20	2.000	1.333	723	195.8	.925	78.9			
	21	1.990	1.340	737	197.4	.719	80.6			
	22	1.985	1.343	714	190.4	1.273	57.2			

[1]Lean blow-out.

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TABLE II. - BASIC DATA FOR COMBUSTION EFFICIENCIES SHOWN IN FIGURES 11 TO 16 - Continued

Figure	Run	Air flow, M_a, lb/sec	Inlet static pressure, P, atm	Inlet mixture temperature, T, °R	Inlet velocity, V, ft/sec	Equivalence ratio	Efficiency, η	Fuel	Injection-system pressure	Configuration
12	42	2.065	1.336	700	195.2	1.002	84.2	Isopentane	Low	VII
	43	2.040	1.333	699	193.0	1.121	77.3			
	44	2.025	1.326	696	191.7	1.238	67.0			
	45	2.020	1.330	711	194.8	1.023	82.6			
	46	2.015	1.333	721	196.5	.919	89.1			
	47	2.010	1.333	730	198.5	.815	92.6			
	48	2.010	1.333	737	200.5	.711	92.4			
	49	2.005	1.340	728	196.6	1.031	83.8			
	50	2.025	1.333	725	198.6	1.128	75.7			
	51	2.025	1.333	717	196.4	1.238	64.3			
	52	2.025	1.333	728	199.4	1.021	84.6			
	53	2.025	1.340	740	201.8	.815	97.1			
	54	2.025	1.333	748	204.9	.713	95.5			
	244	2.145	1.333	696	202.1	0.863	24.3	Isopentane	Low	VIII
	245	2.160	1.347	704	203.5	.759	26.5			
	246	2.160	1.357	704	202.2	.794	27.4			
	247	2.195	1.333	704	209.1	.681	(b)			
	248	2.180	1.333	704	207.6	.908	(a)			
	249	2.185	1.333	710	210.0	.798	25.2			
	250	2.185	1.333	710	210.0	.711	(b)			
13 and 14	359	1.735	1.000	651	203.9	0.774	56.0	Gasoline	High	I
	360	1.735	1.000	651	203.9	.732	(b)			
	361	1.725	1.000	646	201.0	.864	62.9			
	362	1.735	1.000	643	201.4	.946	63.9			
	363	1.720	1.000	641	198.9	1.044	64.6			
	364	1.725	1.000	639	198.8	1.127	61.9			
	365	1.730	1.000	636	198.5	1.217	57.1			
13	589	1.715	1.000	654	202.3	1.184	53.5	Gasoline	High	I[c]
	590	1.710	1.000	656	202.3	1.116	58.4			
	591	1.715	1.003	659	203.2	1.047	60.9			
	592	1.720	1.000	662	205.5	.976	61.0			
	593	1.715	1.000	666	206.2	.914	60.9			
	594	1.715	1.000	669	207.1	.850	59.6			
	595	1.715	1.000	669	207.1	.783	(b)			
	596	1.715	1.000	565	202.9	1.184	55.3			
	597	1.720	1.000	651	202.1	1.248	51.5			
	598	1.715	1.000	647	200.3	1.318	46.6			
	599	1.715	1.000	647	200.3	1.353	(a)			
	600	1.725	1.000	667	207.7	.939	60.2			
	601	1.720	1.000	662	205.5	1.012	61.9			
14	345	1.660	1.000	679	203.4	0.765	85.4	Gasoline	High	VII
	346	1.655	1.000	679	202.8	.724	83.8			
	347	1.655	1.000	679	202.8	.697	(b)			
	348	1.675	1.000	673	203.3	.801	86.4			
	349	1.670	1.000	670	201.8	.850	86.5			
	350	1.675	1.000	666	201.2	.891	86.6			
	351	1.680	1.000	663	201.0	.932	86.4			
	352	1.685	1.000	659	200.3	.974	85.6			
	353	1.690	1.000	656	199.9	1.015	84.3			
	354	1.680	1.013	652	195.0	1.069	81.7			
	355	1.700	1.013	650	196.7	1.100	78.9			
	356	1.690	1.023	644	191.9	1.153	72.9			
	357	1.705	1.023	641	192.7	1.189	69.5			
	381	1.670	1.000	659	198.6	.892	80.1			
	382	1.675	1.000	663	200.4	0.846	82.1	Gasoline	High	VII[d]
	383	1.665	1.000	667	200.3	.808	82.7			
	384	1.665	1.000	670	201.4	.763	82.3			
	385	1.665	1.000	670	201.4	.748	(b)			
	386	1.655	1.000	666	199.0	.994	80.8			
	387	1.655	1.000	662	197.8	1.084	77.6			
	388	1.665	1.000	658	197.7	1.171	70.3			
	389	1.655	1.000	654	195.4	1.273	61.0			
	390	1.655	1.000	654	195.4	1.321	(a)			
	391	1.650	1.000	668	199.0	1.040	80.0			
	392	1.660	1.000	672	201.3	.942	83.6			
	393	1.660	1.000	664	198.8	1.129	73.0			
	394	1.655	1.000	660	197.2	1.228	65.2			
	395	1.655	1.000	660	197.2	1.316	(a)			

[a]Rich blow-out.
[b]Lean blow-out.
[c]V-gutter 2" wide by 2" high.
[d]Cooled blades.

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TABLE II. - BASIC DATA FOR COMBUSTION EFFICIENCIES SHOWN IN FIGURES 11 TO 16 - Concluded

Figure	Run	Air flow, M_a, lb/sec	Inlet static pressure, P, atm	Inlet mixture temperature, T, °R	Inlet velocity, V, ft/sec	Equivalence ratio	Efficiency, η	Fuel	Injection-system pressure	Configuration
15 and 16	623	1.145	0.666	658	203.8	1.048	69.4	Gasoline	High	VII
	624	1.145	.666	654	202.6	1.110	66.7			
	625	1.145	.666	650	201.4	1.172	62.0			
	626	1.145	.666	650	201.4	1.240	(a)			
	627	1.150	.666	655	203.9	1.044	70.3			
	628	1.145	.666	658	203.8	.986	74.4			
	629	1.145	.666	660	204.6	.924	77.2			
	630	1.145	.666	662	205.2	.862	78.5			
	631	1.160	.666	665	208.9	.790	78.4			
15	366	1.125	0.666	653	198.7	0.944	58.3	Gasoline	High	I
	367	1.120	.666	652	197.7	.885	57.7			
	368	1.120	.666	654	198.3	.819	53.8			
	369	1.120	.666	654	198.3	.777	(b)			
	370	1.120	.666	647	196.2	1.008	59.3			
	371	1.110	.666	644	193.5	1.081	59.7			
	372	1.120	.666	641	194.4	1.133	57.3			
	373	1.120	.666	638	193.5	1.201	53.1			
	374	1.120	.666	635	192.6	1.264	49.6			
	375	1.120	.666	635	192.6	1.339	(a)			
16	632	1.160	0.666	665	208.9	0.734	(b)	Gasoline	High	VII
	633	.765	.443	653	203.3	1.100	64.1			
	634	.765	.450	653	200.2	1.149	(a)			
	635	.760	.450	652	198.8	1.058	65.7			
	636	.765	.453	653	198.9	1.002	66.9			
	637	.760	.450	656	199.8	.954	69.7			
	638	.760	.450	656	199.8	.954	(b)			
	640	0.850	0.500	656	201.3	1.078	65.1	Gasoline	High	VII
	641	.850	.500	654	200.5	1.118	64.0			
	642	.850	.500	651	199.8	1.162	61.5			
	643	.850	.500	651	199.8	1.206	58.6			
	644	.850	.500	651	199.8	1.245	(a)			
	645	.850	.500	660	202.5	1.078	65.9			
	646	.850	.500	661	202.7	1.035	69.1			
	647	.850	.500	662	203.1	.990	70.1			
	648	.850	.500	663	203.4	.946	71.6			
	649	.850	.503	665	202.7	.902	72.6			
	650	.850	.503	668	203.5	.854	73.2			
	651	.850	.500	668	204.8	.838	(b)			
	652	1.740	1.000	696	218.6	0.771	79.7	Gasoline	High	VII
	653	1.735	1.000	691	216.2	.819	82.2			
	654	1.735	1.000	687	215.7	.860	80.8			
	655	1.735	1.000	685	214.5	.903	82.0			
	656	1.740	1.000	682	214.0	.944	81.2			
	657	1.740	1.000	679	213.2	.988	79.1			
	658	1.740	1.000	677	212.6	1.032	76.7			
	659	1.740	1.000	672	211.0	1.120	69.9			
	660	1.740	1.000	668	209.7	1.212	62.0			
	661	1.745	1.000	662	208.3	1.296	53.2			
	662	1.745	1.000	662	208.3	1.344	(a)			
	663	1.740	1.000	687	215.6	.771	81.4			
	664	1.740	1.000	688	215.9	.730	80.8			
	665	1.740	1.000	688	215.9	.686	(b)			
	666	1.440	0.833	682	212.6	0.732	77.5	Gasoline	High	VII
	667	1.450	.833	676	212.3	1.005	76.3			
	668	1.440	.833	672	209.5	1.088	71.8			
	669	1.430	.833	668	206.9	1.174	65.2			
	670	1.440	.833	664	207.1	1.246	57.2			

[a]Rich blow-out.
[b]Lean blow-out.

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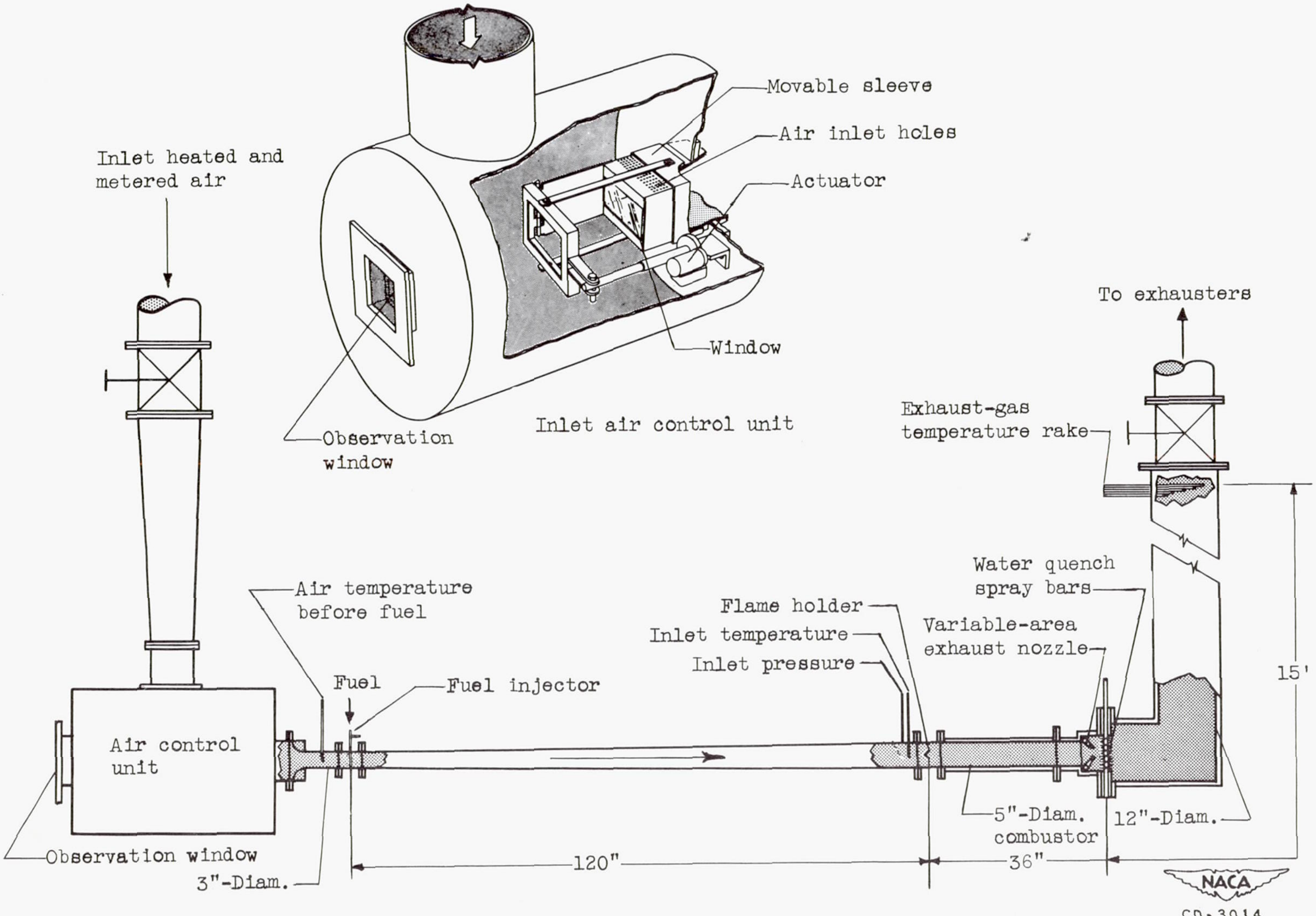

Figure 1. - Schematic illustration of 5-inch ram-jet combustor setup.

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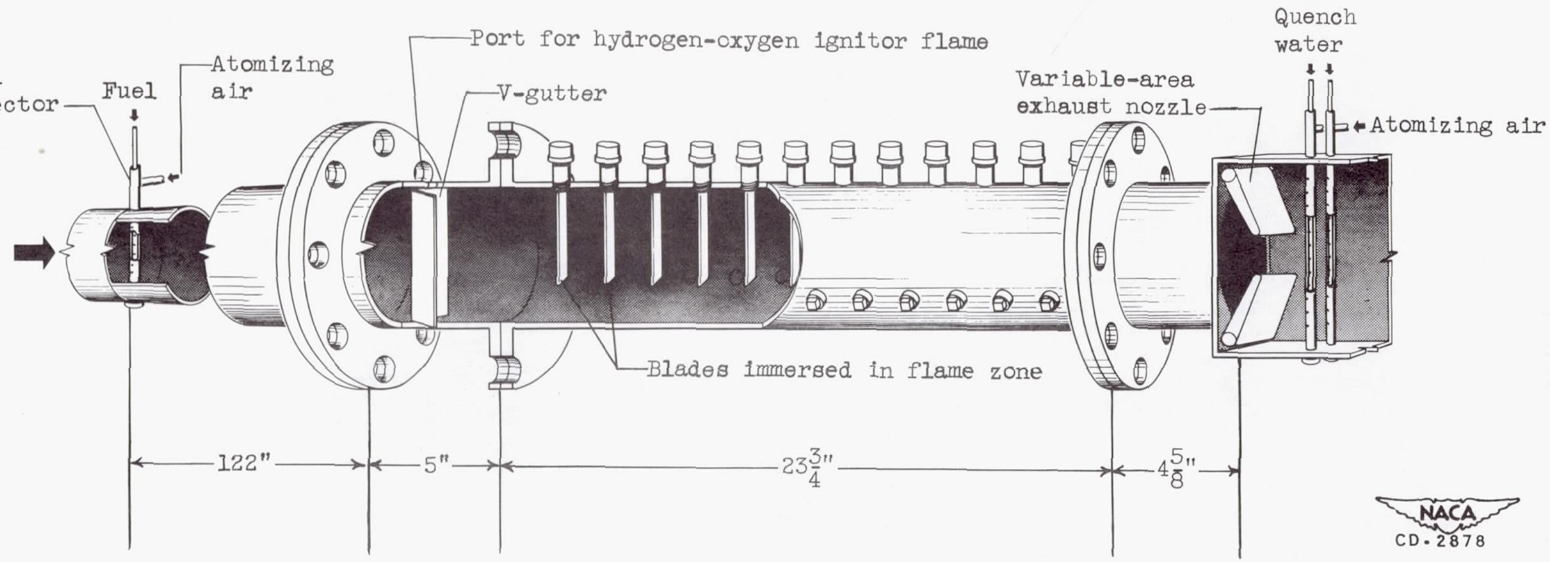

Figure 2. - Five-inch-diameter, connected-pipe, ram-jet combustor.

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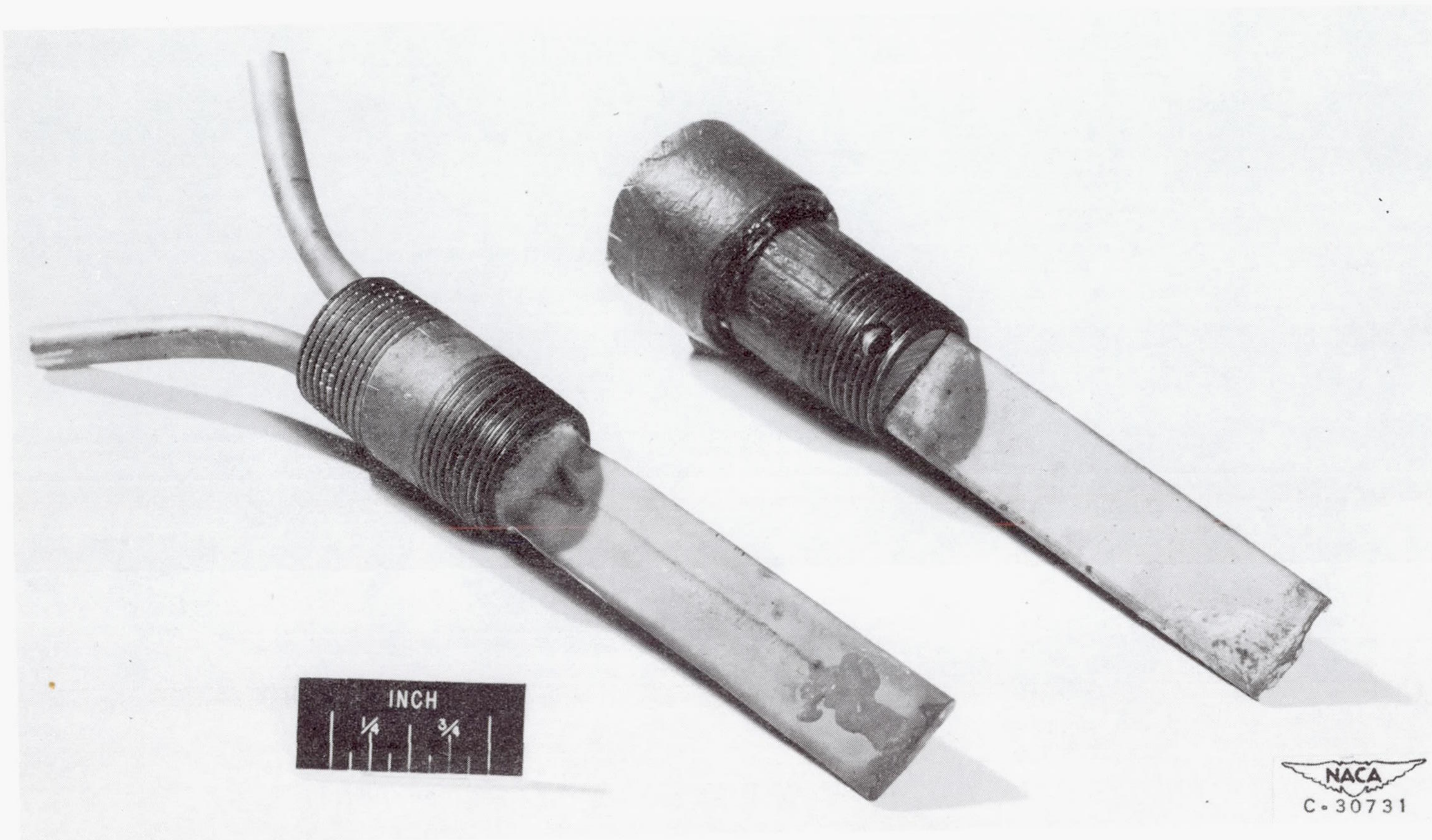

(a) Inconel blade, internally water cooled.

(b) Molybdenum blade, refractory and oxidation resistant up to 3000° F.

Figure 3. - Photograph of two types of flame-immersed blade used in 5-inch-diameter ram-jet combustor.

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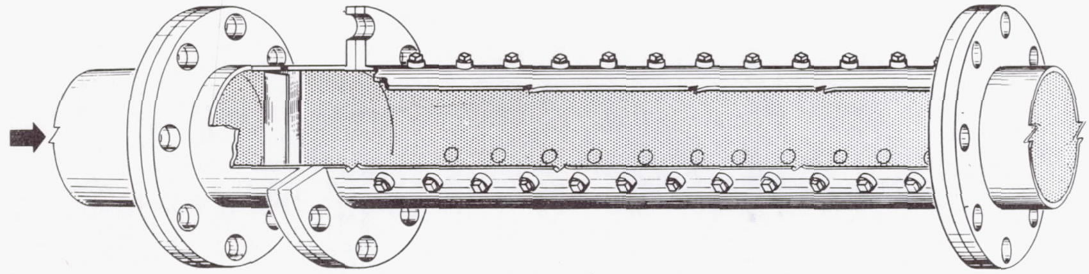
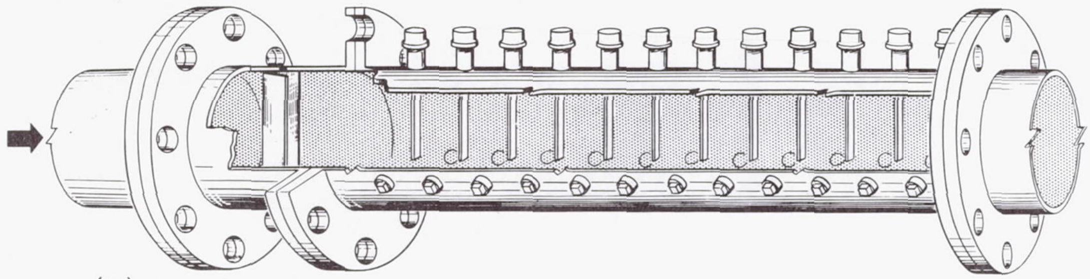
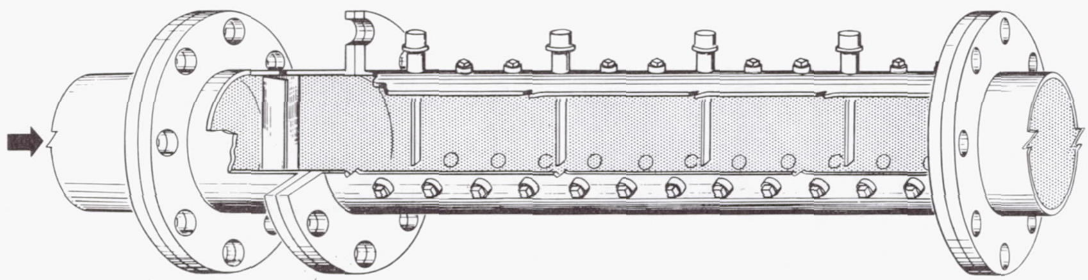


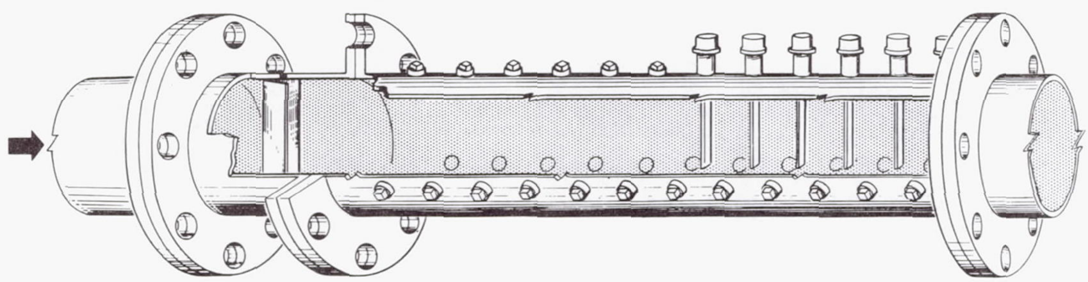
(a) Configuration I; V-gutter alone.



(b) Configuration II; 12 blades in line and perpendicular to axis.



(c) Configuration III; blades in positions 1, 4, 7, and 10.



(d) Configuration IV; blades in positions 7 to 12.

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Figure 4. - Various geometrical configurations used in investigation.

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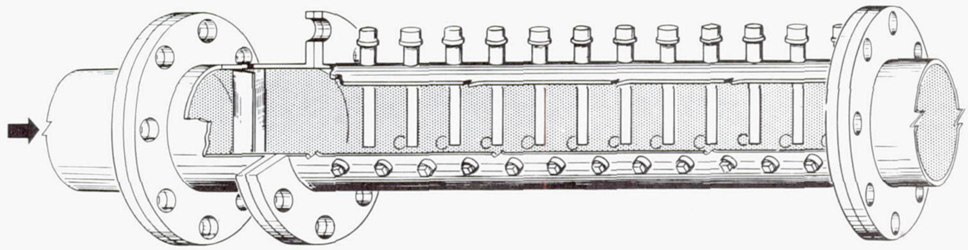
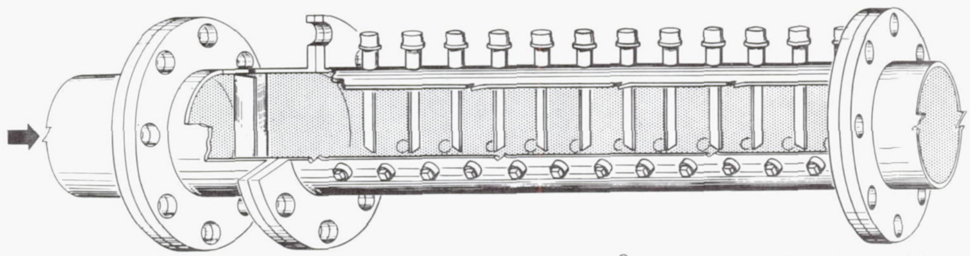
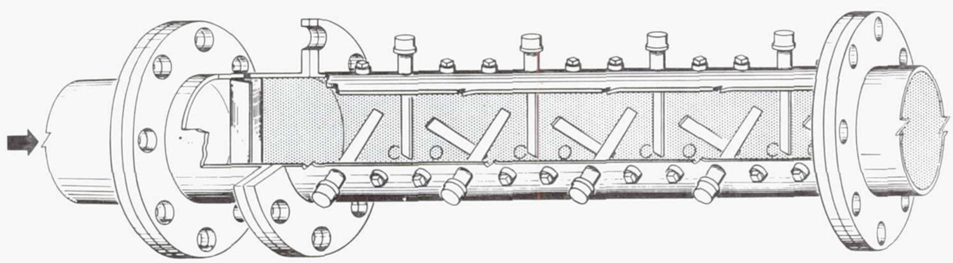


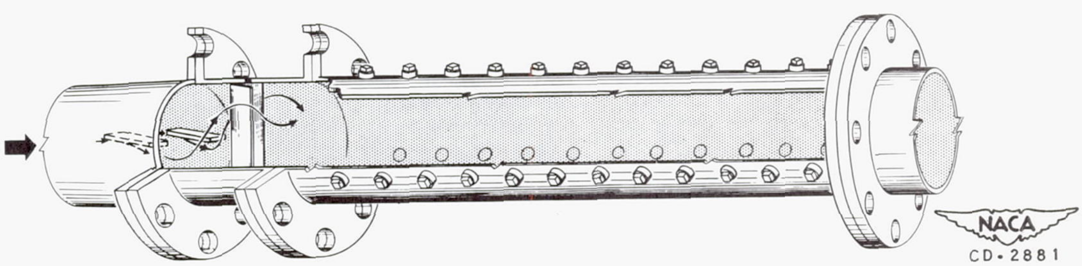
(e) Configuration V; 12 blades in line and parallel to axis.



(f) Configuration VI; 12 blades turned 45° to axis and alternating.



(g) Configuration VII; 12 blades positioned for mixing.



(h) Configuration VIII; vortex generators upstream of V-gutter.

Figure 4. - Concluded. Various geometrical configurations used in investigation.

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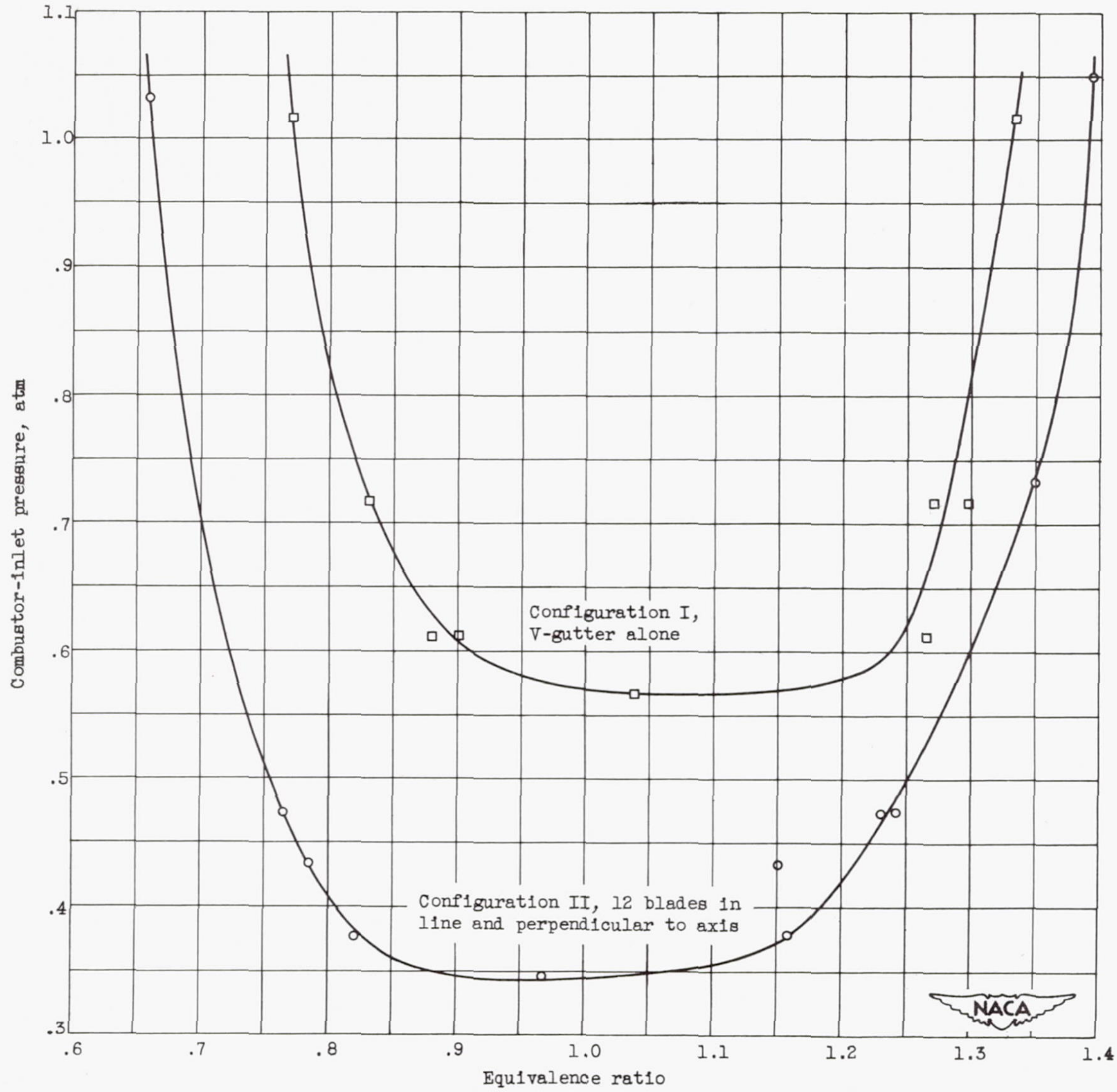

Figure 5. - Comparison of combustion limits of configurations I and II. Inlet conditions: temperature, 200° F; velocity, 220 feet per second. Fuel, isopentane with low-pressure injection.

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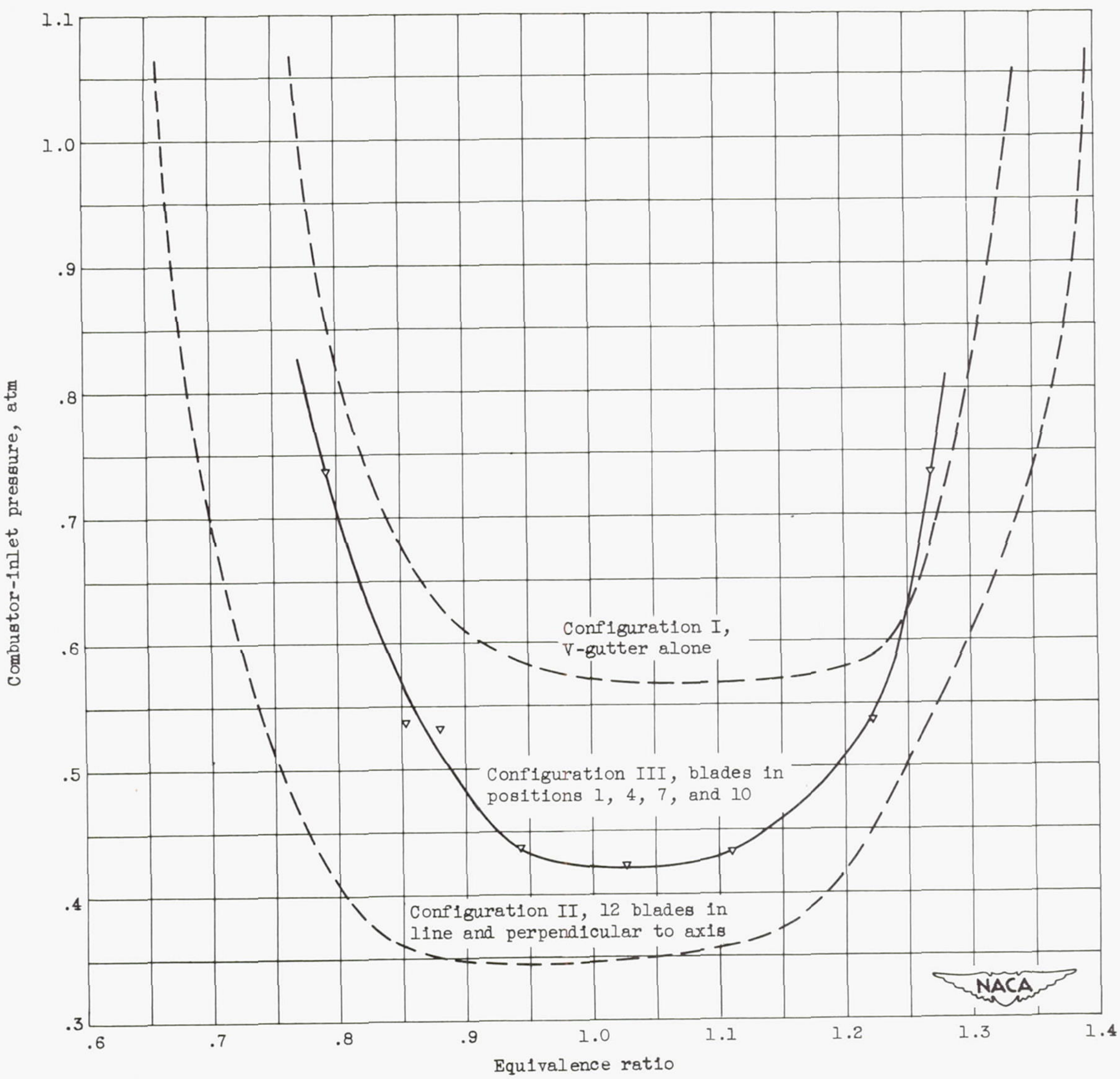

(a) Configuration III.

Figure 6. - Comparison of combustion limits of several configurations with combustion limits of configurations I and II as shown in figure 5. Inlet conditions: temperature, 200° F; velocity, 220 feet per second. Fuel, isopentane with low-pressure injection.

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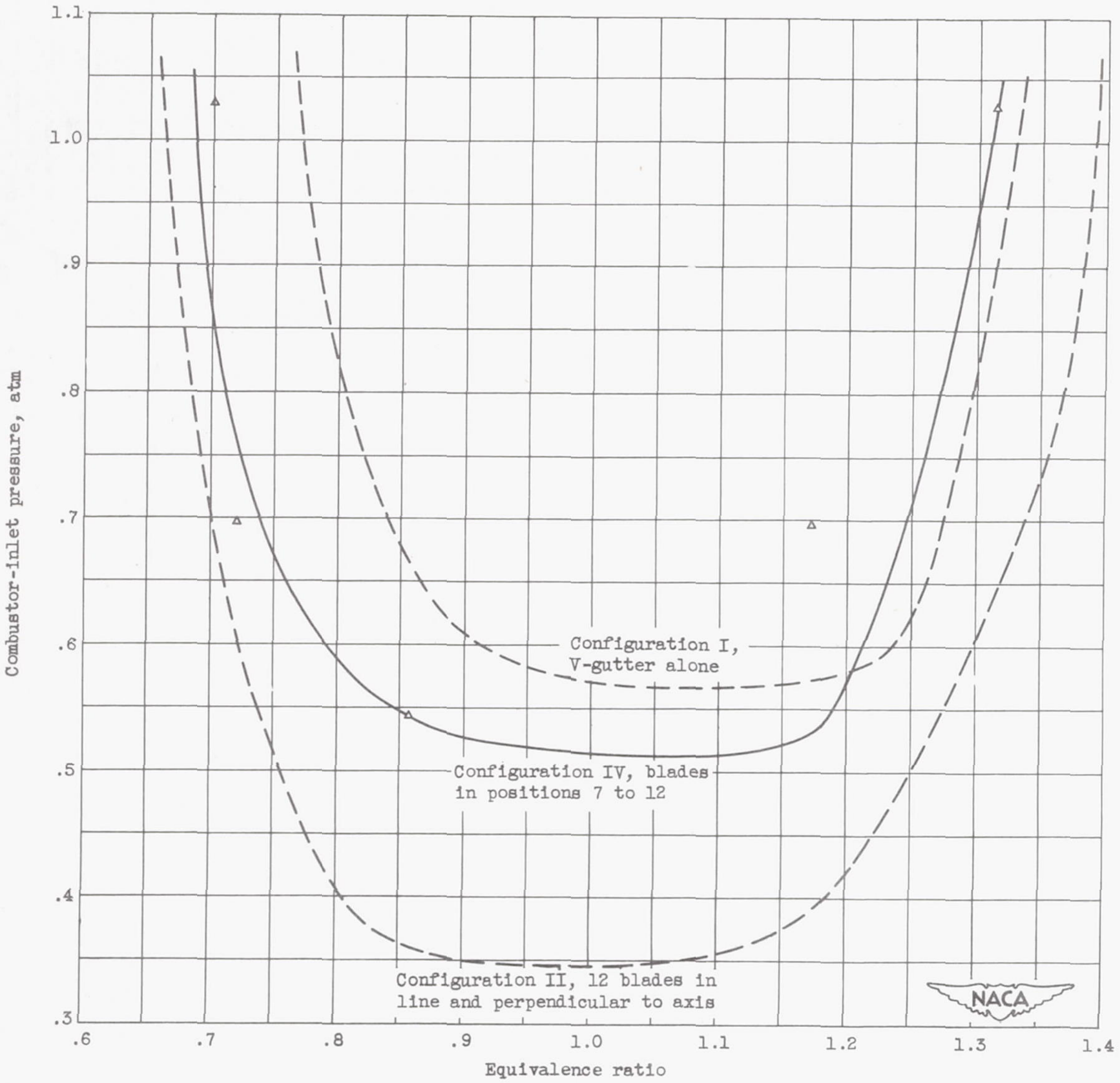

(b) Configuration IV.

Figure 6. - Continued. Comparison of combustion limits of several configurations with combustion limits of configurations I and II as shown in figure 5. Inlet conditions: temperature, 200° F; velocity, 220 feet per second. Fuel, isopentane with low-pressure injection.

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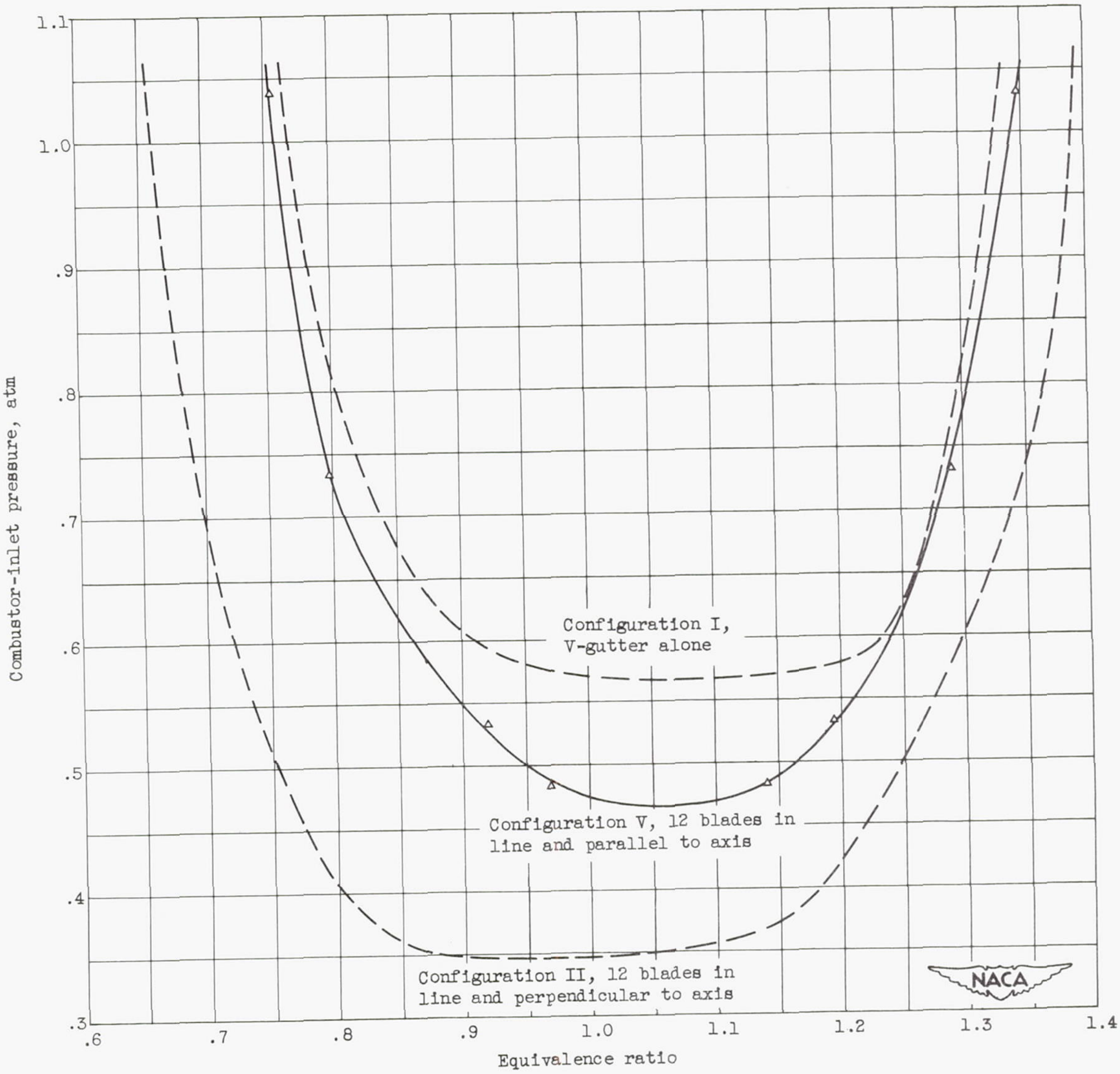

(c) Configuration V.

Figure 6. - Continued. Comparison of combustion limits of several configurations with combustion limits of configurations I and II as shown in figure 5. Inlet conditions: temperature, 200° F; velocity, 220 feet per second. Fuel, isopentane with low-pressure injection.

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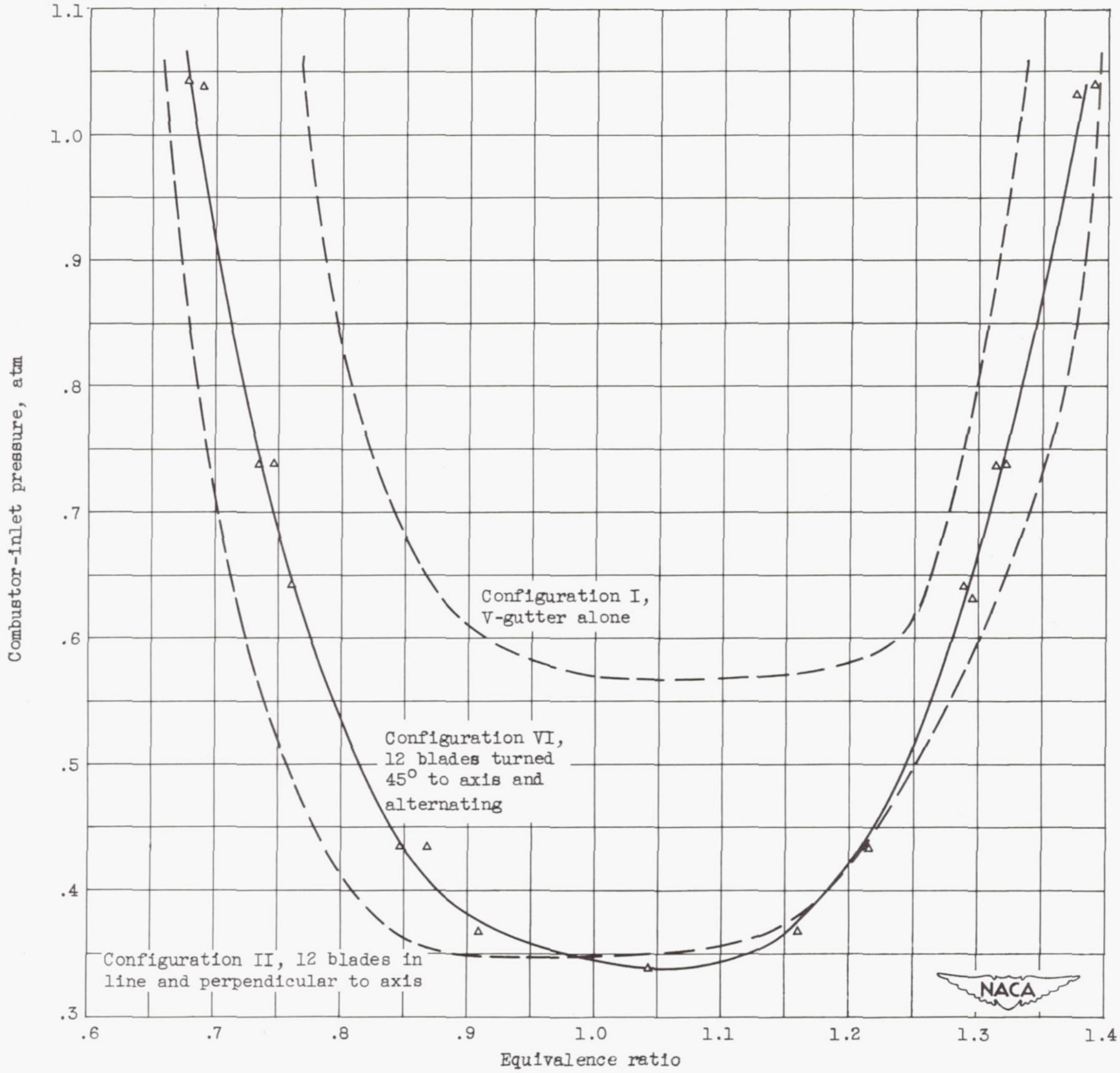

(d) Configuration VI.

Figure 6. - Concluded. Comparison of combustion limits of several configurations with combustion limits of configurations I and II as shown in figure 5. Inlet conditions: temperature, 200° F; velocity, 220 feet per second. Fuel, isopentane with low-pressure injection.

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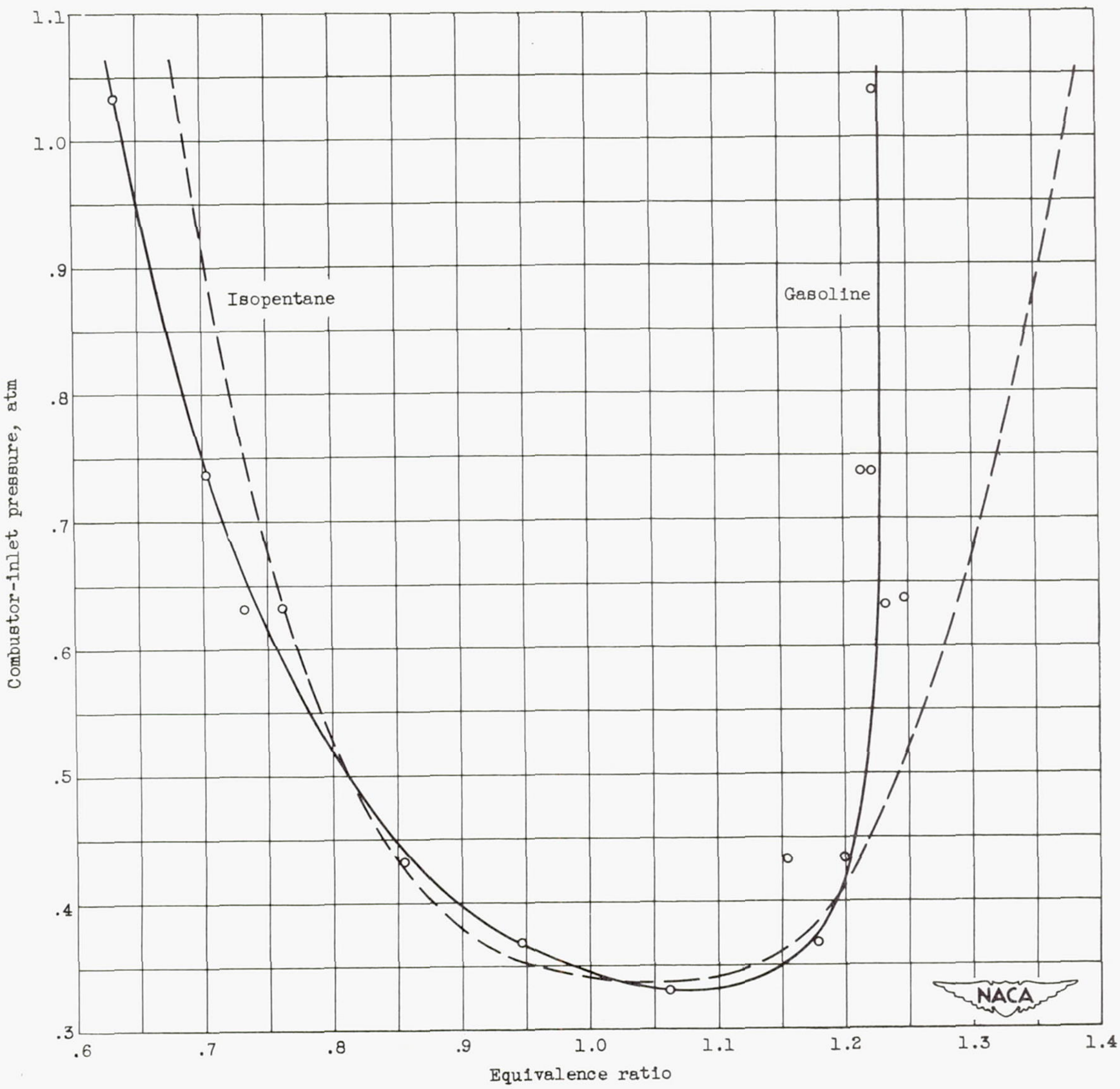

Figure 7. - Comparison of combustion limits of gasoline and isopentane in configuration VI. Inlet conditions: temperature, 160° F; velocity, 220 feet per second. Low-pressure fuel injection.

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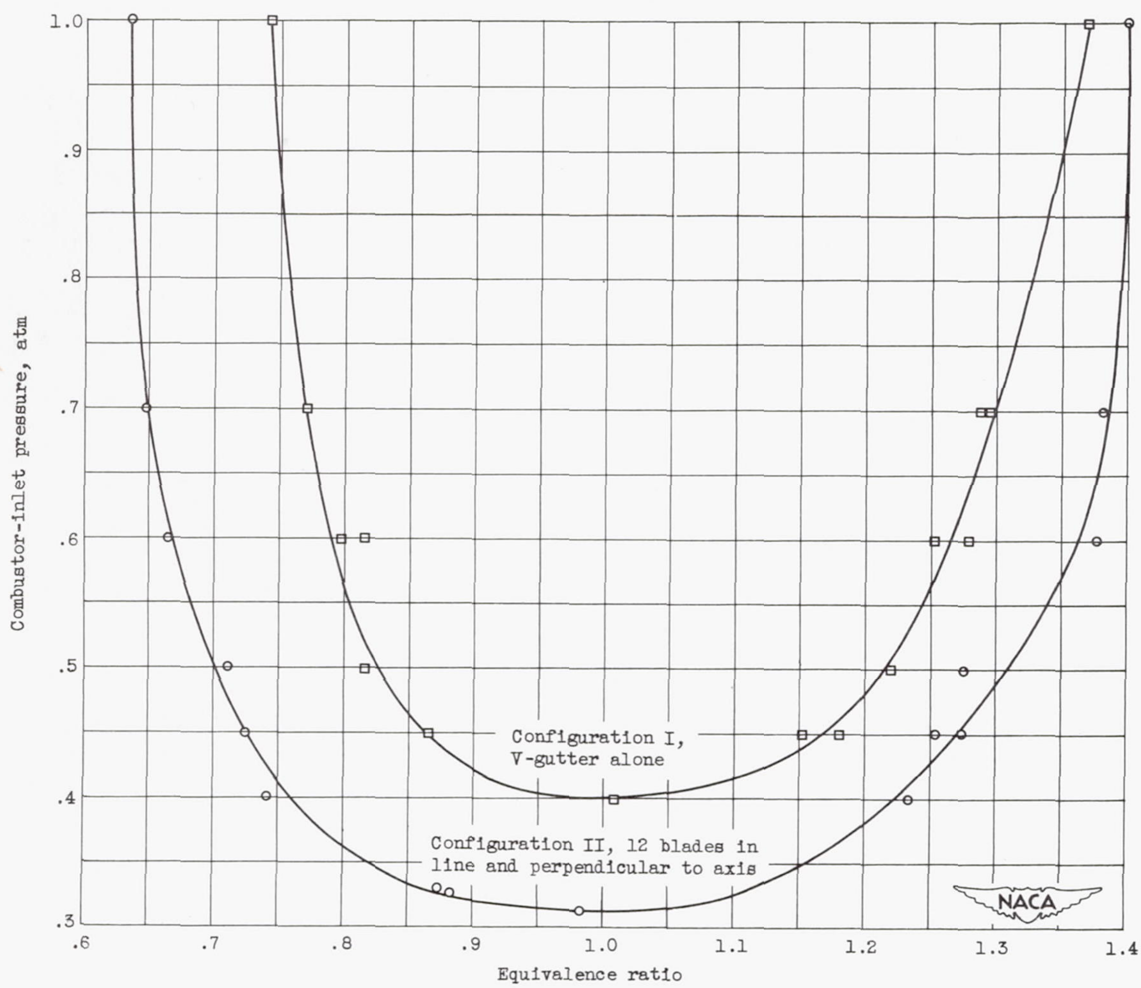

Figure 8. - Combustion limits of configurations I and II. Inlet conditions: temperature, 200° F; velocity, 200 feet per second. Fuel, gasoline with high-pressure injection.

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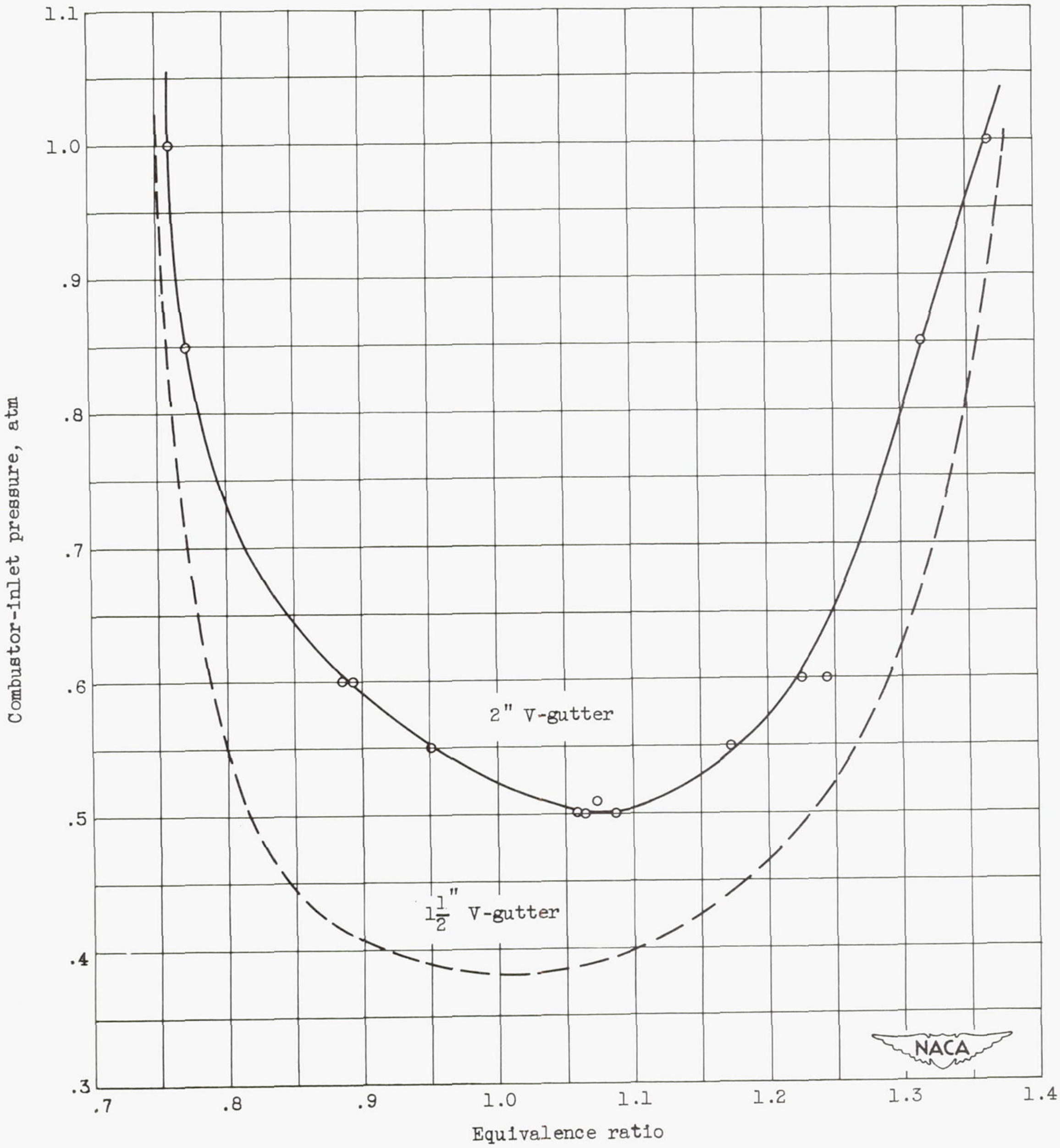

Figure 9. - Combustion limits of 2- and $1\frac{1}{2}$-inch V-gutters. Inlet conditions: temperature, 200° F; velocity, 200 feet per second. Fuel, gasoline with high-pressure injection.

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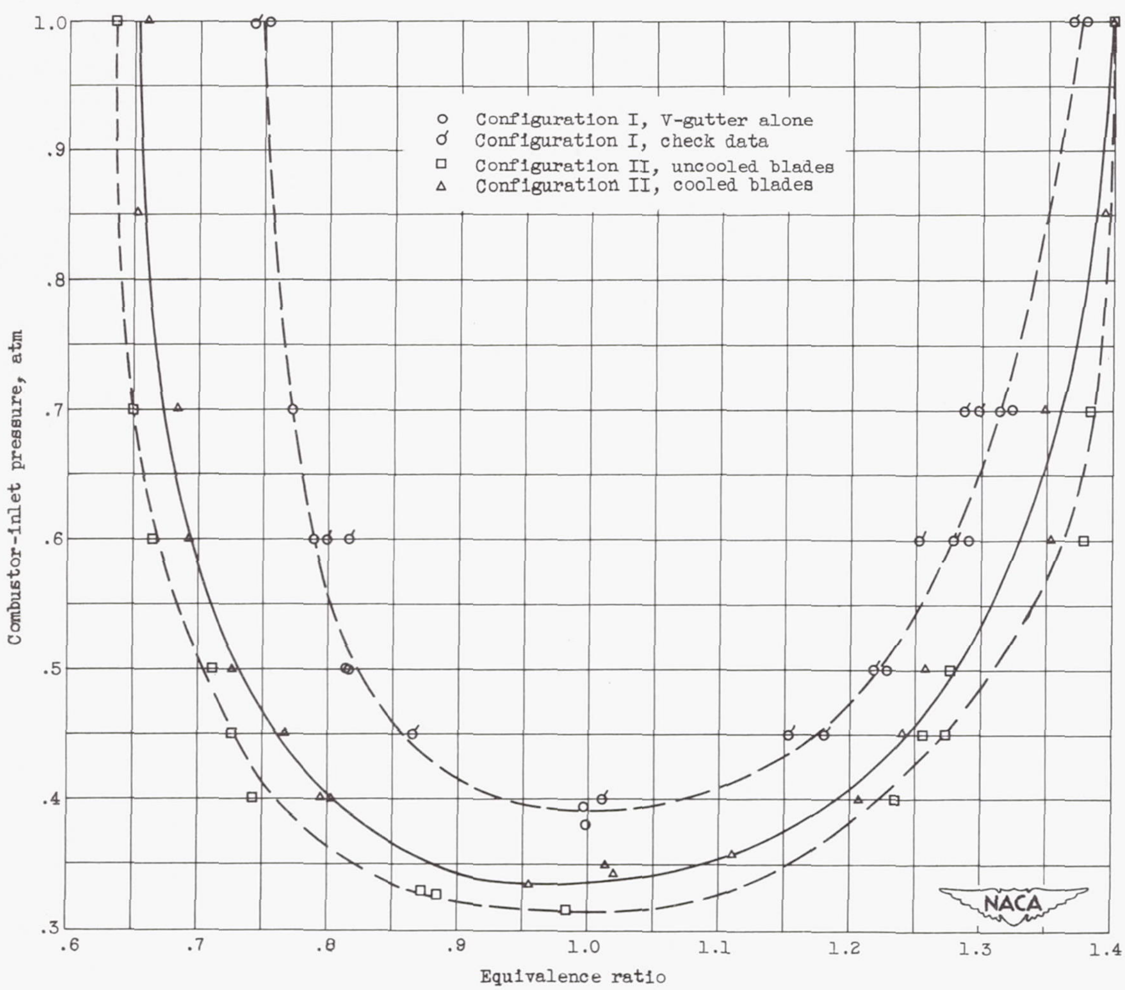

Figure 10. - Combustion limits of configuration I and of configuration II with both cooled and uncooled blades. Inlet conditions: temperature, 200° F; velocity, 230 feet per second. Fuel, gasoline with high-pressure injection.

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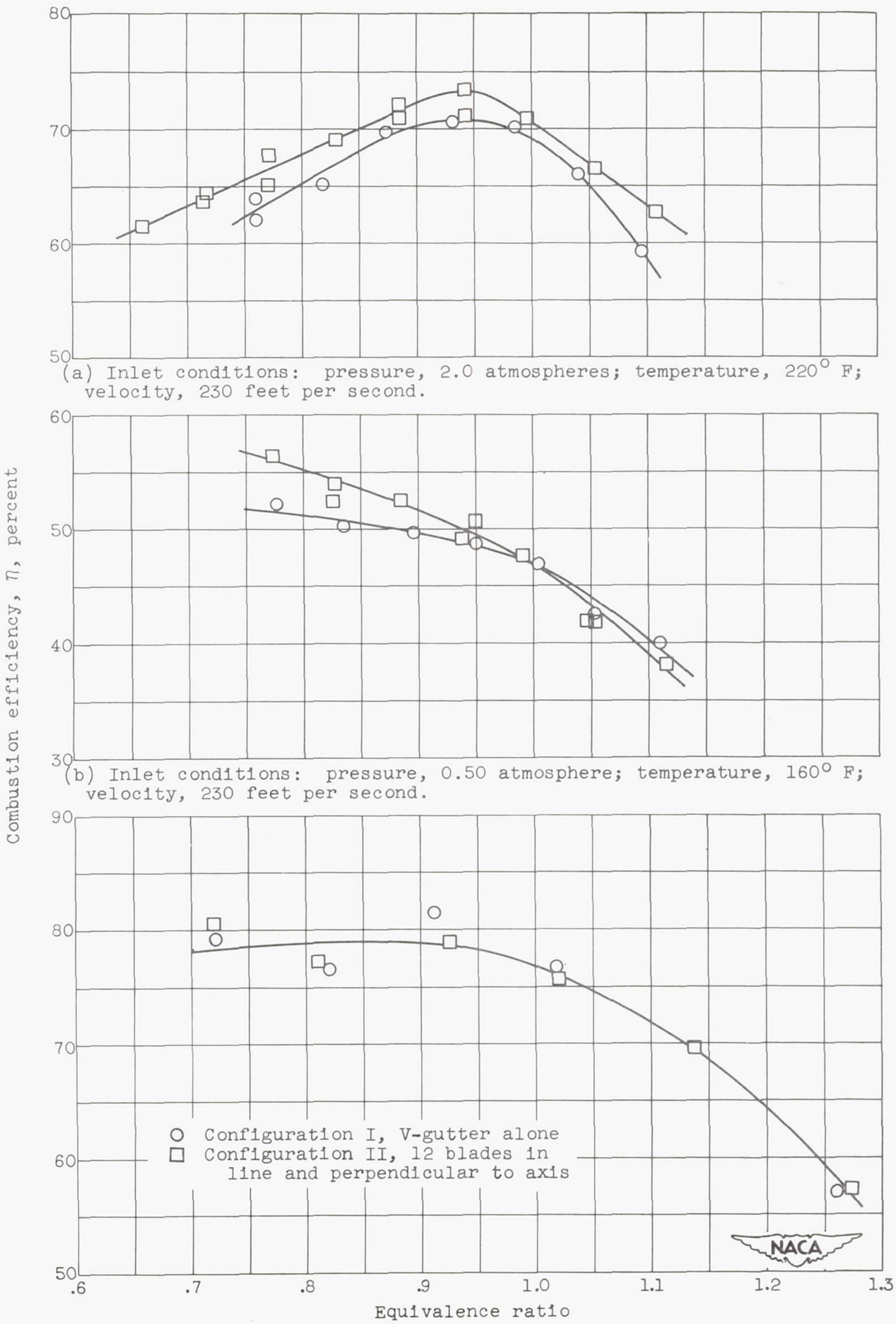

(a) Inlet conditions: pressure, 2.0 atmospheres; temperature, 220° F; velocity, 230 feet per second.

(b) Inlet conditions: pressure, 0.50 atmosphere; temperature, 160° F; velocity, 230 feet per second.

(c) Inlet conditions: pressure, 1.33 atmospheres; temperature, 260° F; velocity, 200 feet per second.

Figure 11. - Combustion efficiencies of configurations I and II at several inlet conditions. Fuel, isopentane with low-pressure injection.

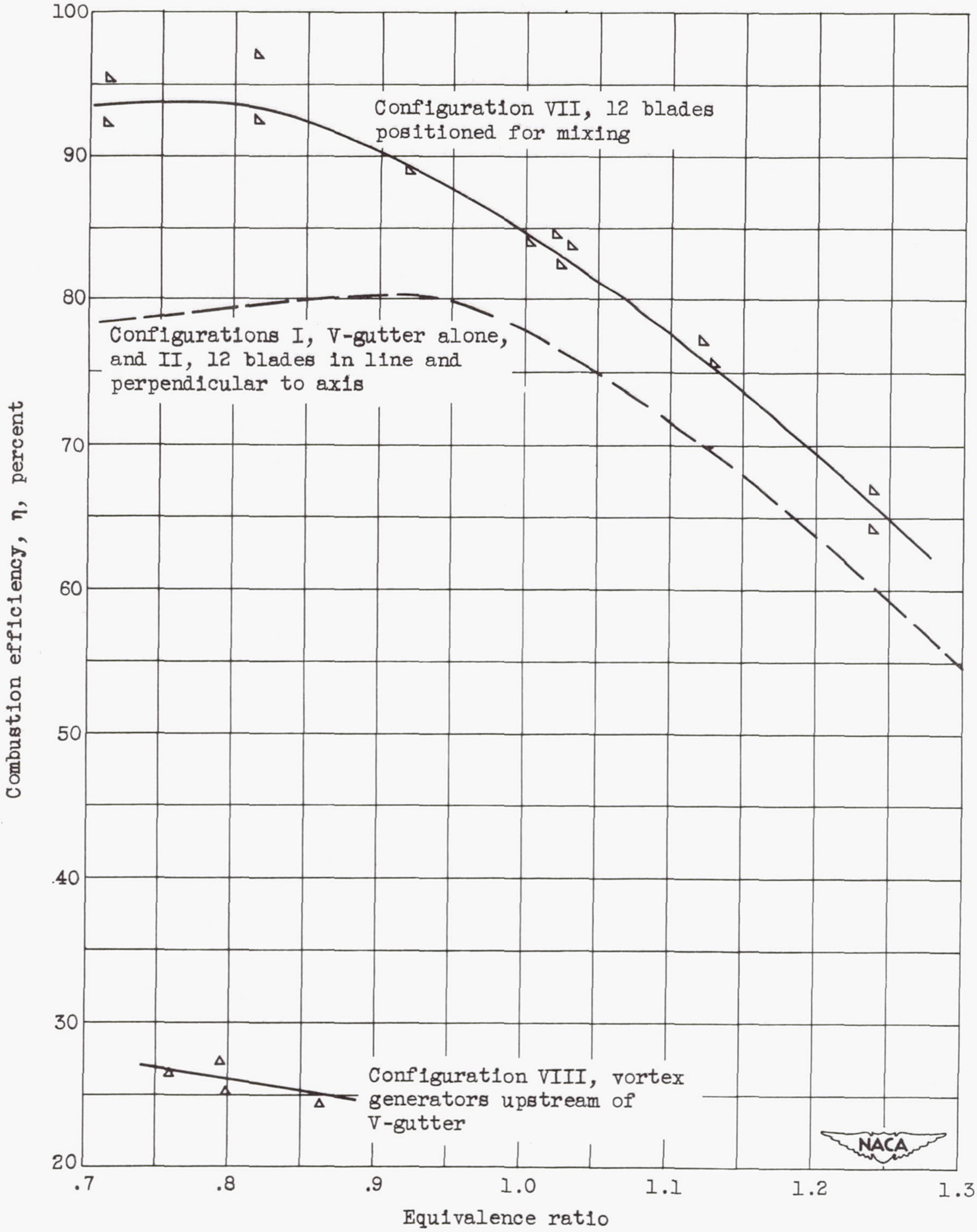

Figure 12. - Combustion efficiencies of configurations I, II, VII, and VIII. Inlet conditions: pressure, 1.33 atmospheres; temperature, 250° F; velocity, 200 feet per second. Fuel, isopentane with low-pressure injection.

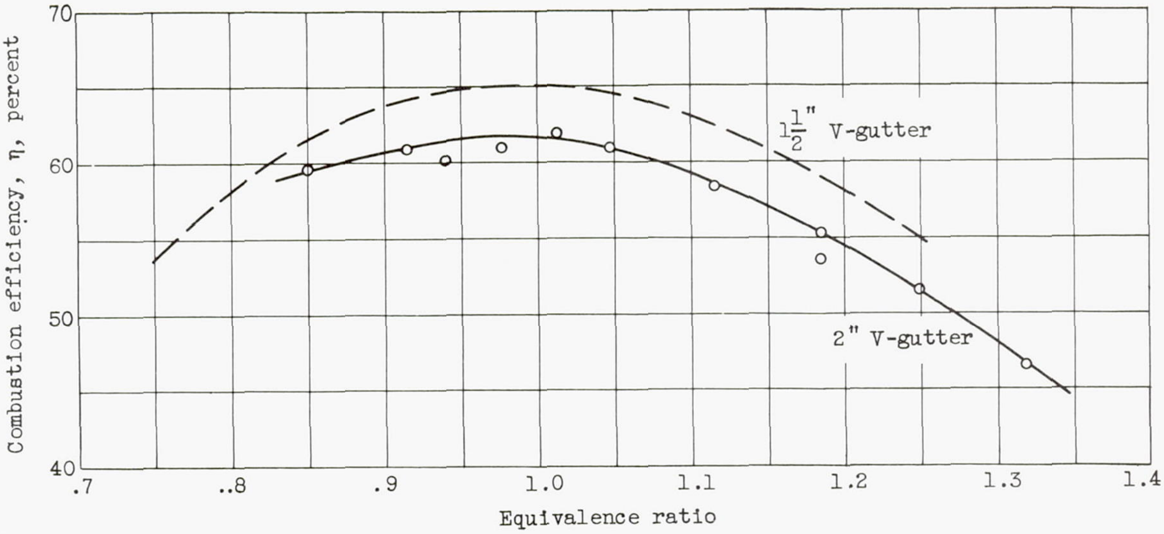

Figure 13. - Combustion efficiencies of $1\frac{1}{2}$- and 2-inch V-gutters. Inlet conditions: pressure, 1 atmosphere; temperature, 200° F; velocity, 200 feet per second. Fuel, gasoline with high-pressure injection.

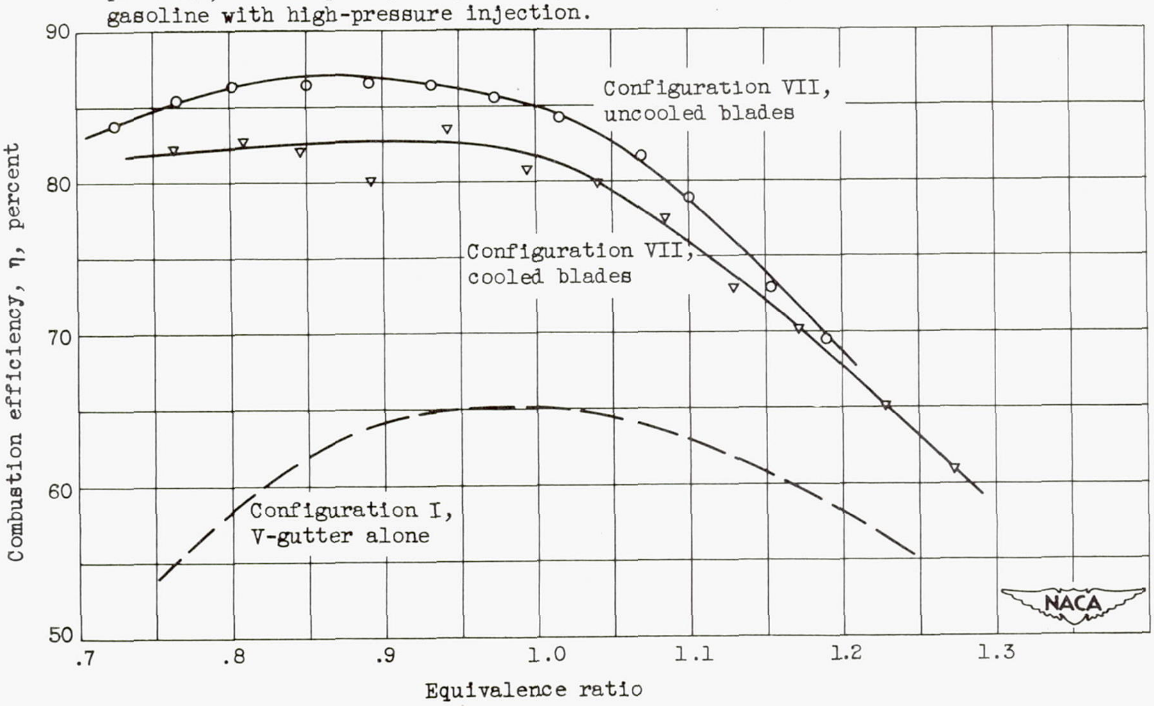

Figure 14. - Combustion efficiencies of configuration I and of configuration VII with both cooled and uncooled blades. Inlet conditions: pressure, 1 atmosphere; temperature, 200° F; velocity, 200 feet per second. Fuel, gasoline with high-pressure injection.

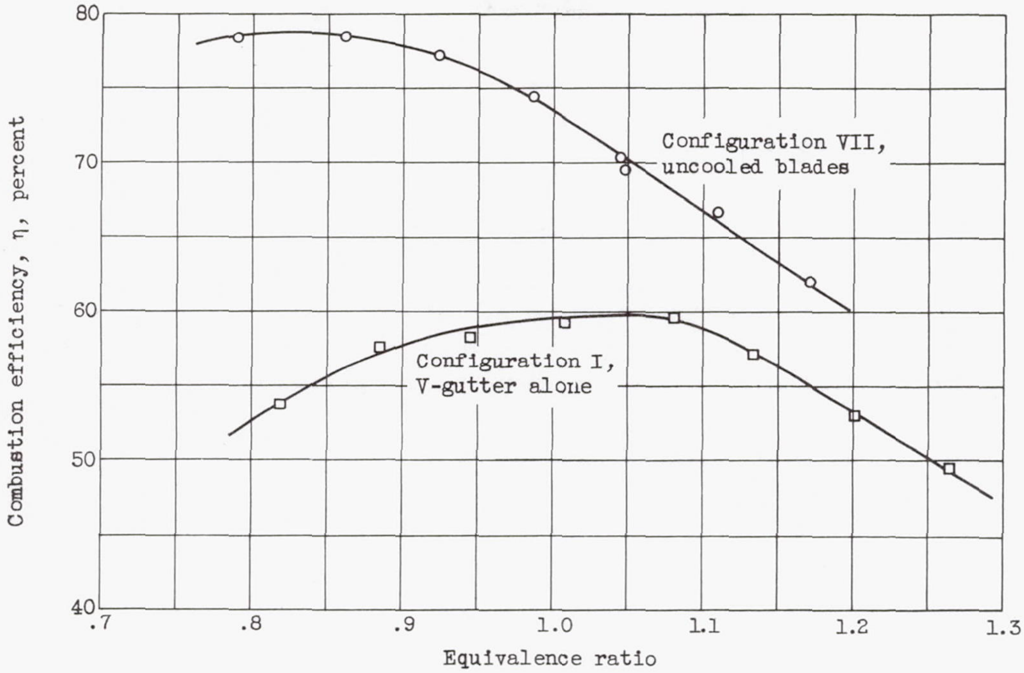

Figure 15. - Combustion efficiencies of configurations I and VII. Inlet conditions: pressure, 0.67 atmosphere; temperature, 200° F; velocity, 200 feet per second. Fuel, gasoline with high-pressure injection.

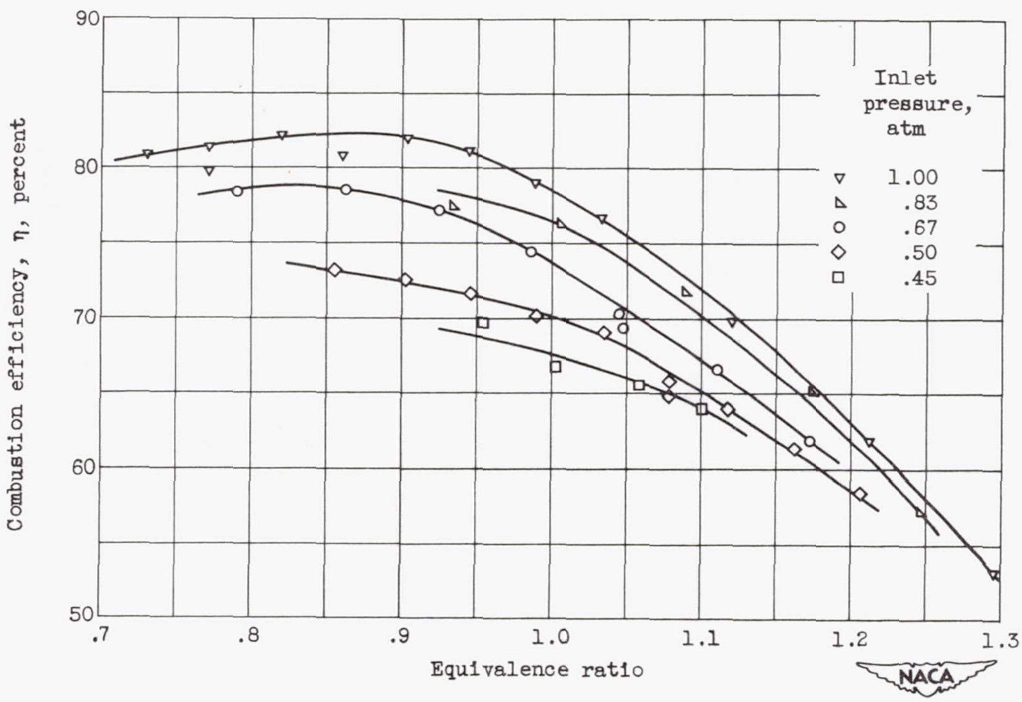

Figure 16. - Combustion efficiencies of configuration VII at several inlet pressures. Inlet conditions: temperature, 200° F; velocity, 200 feet per second. Fuel, gasoline with high-pressure injection.

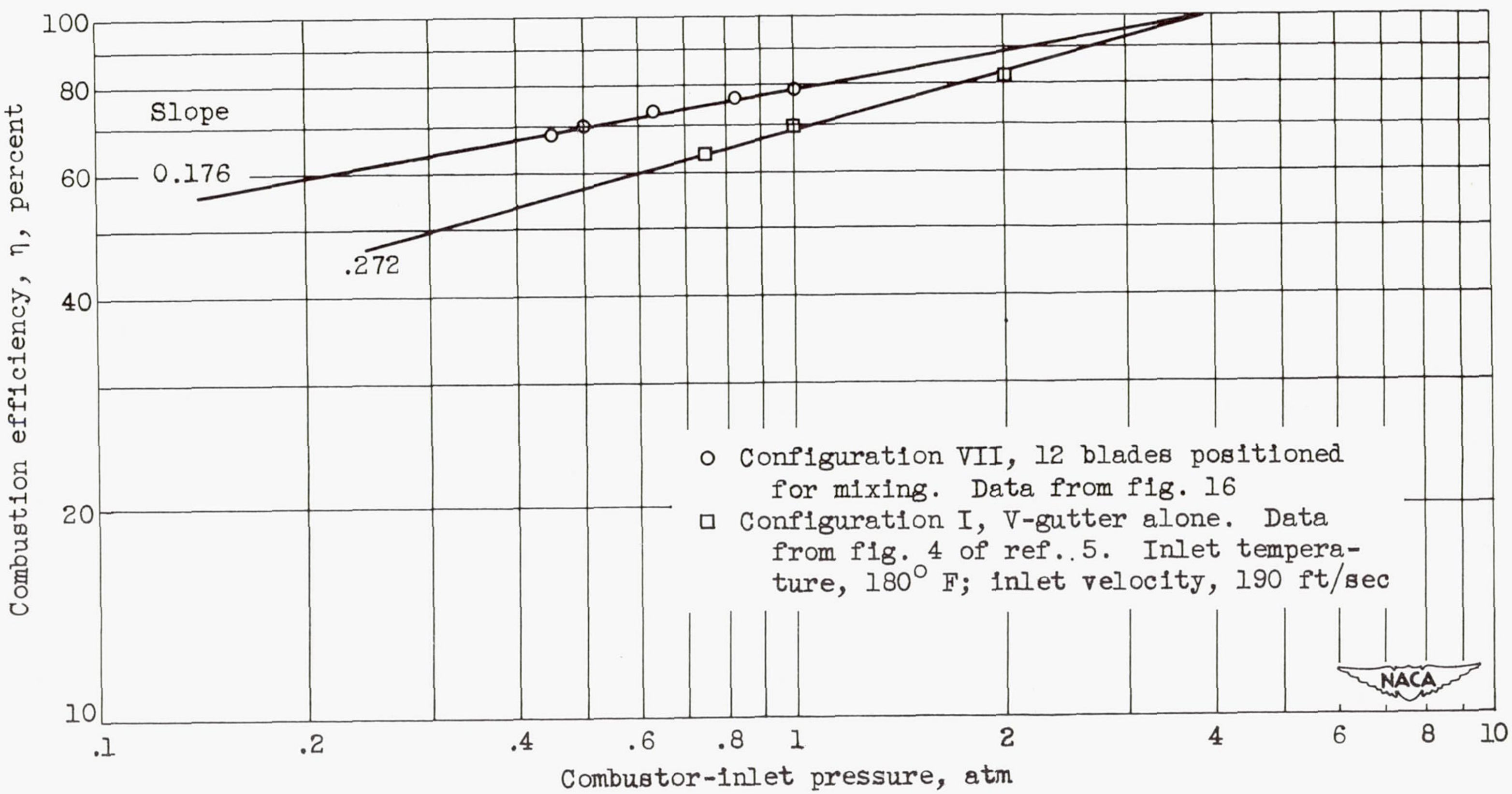

Figure 17. - Comparison of variation of combustion efficiency with inlet pressure of configurations I and VII.

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